



DONALD CARTER

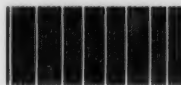


CONSULTANTS

CA1
DTC800
90
P17

CA1
DTC800-
90
P17
C.2

436802



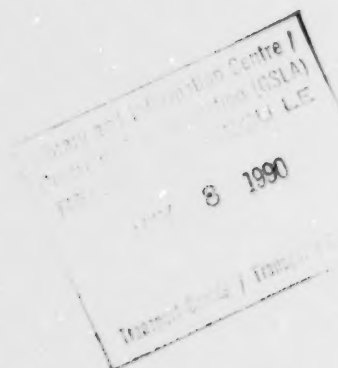
41.D

90-07195/

CA1
DTC 800
90
P17
C.2

PARAMETRIC STUDY OF
ICEBREAKING BOW FORMS
TP-10193E

prepared for
TRANSPORTATION DEVELOPMENT CENTRE
POLICY AND COORDINATION GROUP
TRANSPORT CANADA
March 1990



prepared by

Donald Carter, P.Eng., D.Sc.

DONALD CARTER & Associates,
CONSULTANTS,
1281 Bishop, Ste Foy,
Quebec, G1W 3E4

436802

DISCLAIMER

The contents of this report reflect the views of the contractor and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

LANGUAGE NOTICE

Un sommaire en français de ce rapport est inclus avant la Table des matières.

PROJECT TEAM

The project team included:
Donald Carter, P.Eng., D.Sc.
Réjean Desgagnés, Naval Architect
Jean P. Charest, Technician in Naval Architecture
G. Carbonneau, Typist

1. Transport Canada Publication No. TP 10193E		2. Project No. 7136		3. Recipient's Catalogue No.	
4. Title and Subtitle PARAMETRIC STUDY OF ICEBREAKING BOW FORMS				5. Publication Date March 1990	
				6. Performing Organization Document No.	
7. Author(s) Donald Carter				8. Transport Canada File No. D1460-177-3	
9. Performing Organization Name and Address DONALD CARTER & Associates, Consultants 1281 Bishop Ste-Foy, Quebec, G1W 3E4				10. DSS File No. 16SD-T8200-8-8528	
				11. DSS or Transport Canada Contract No. T8200-8-8523/01-SD	
12. Sponsoring Agency Name and Address Transportation Development Centre, 200 René Lévesque Blvd West, Suite 601, West Tower, Montreal Quebec, H2Z 1X4				13. Type of Publication and Period Covered Final, Dec.88-March90	
				14. Project Officer J.E. Laframboise	
15. Supplementary Notes (Funding programs, titles of related publications, etc.)					
16. Abstract The report presents an overview of the Carter's math model, along with its rationale, assumptions, simplifications and limitations. The validity of the predictive model is substantiated by relevant results of laboratory and field tests. By using a computer program that facilitates problem solution, a systematic variation is made of all ice and ship parameters involved in breaking and moving through level ice. The analytical treatment of the hull-ice interactions over the forebody not only presents a method for evaluating the total icebreaking resistance, but also provides the ship designer with a meaningful design tool for optimizing ice passage capability. A series of 3 bows have been designed to illustrate that, by maintaining an optimum relationship between the waterline and flare angles at discrete positions on the bow, it is possible to greatly improve the icebreaking efficiency without unduly affecting the open water performance. The predicted level ice resistance for the 3 proposed bows shows a significant improvement over the R-Class Icebreaker.					
17. Key Words Level ice resistance Icebreaking bows Mathematical model			18. Distribution Statement Limited number of copies available from the Transportation Development Centre		
19. Security Classification (of this publication) Unclassified		20. Security Classification (of this page) Unclassified		21. Declassification (date)	22. No. of Pages 87
				23. Price	

1. N° de la publication de Transports Canada TP 10193E	2. N° de l'étude 7136	3. N° de catalogue du destinataire		
4. Titre et sous-titre PARAMETRIC STUDY OF ICEBREAKING BOW FORMS		5. Date de la publication Mars 1990		
		6. N° du document de l'organisme exécutant		
7. Auteur(s) Donald Carter		8. N° de dossier — Transports Canada D1460-177-3		
9. Nom et adresse de l'organisme exécutant DONALD CARTER & Associés Consultants 1281 Bishop Ste-Foy (Québec) G1W 3E4		10. N° de dossier — ASC 16SD-T8200-8-8528		
		11. N° de contrat — ASC ou Transports Canada T8200-8-8523/01-SD		
12. Nom et adresse de l'organisme parrain Centre de développement des transports, Complexe Guy-Favreau, Suite 601, tour ouest, 200 ouest, boul. René Lévesque, Montréal (Québec) H2Z 1X4		13. Genre de publication et période visée Rapport final, Mars 90		
		14. Agent de projet J.E. Laframboise		
15. Remarques additionnelles (Programmes de financement, titres de publications connexes, etc.)				
16. Résumé Le présent rapport présente un survol du modèle mathématique développé par Carter, avec ses justifications, ses hypothèses, ses simplifications et ses limites. La validité du modèle est corroborée par des résultats obtenus en laboratoire et en nature. En se servant d'un programme informatisé qui facilite la solution du problème, une variation systématique est faite de tous les paramètres du navire et de la glace qui interviennent lors du passage d'un navire dans un champ de glace. Le traitement analytique des interactions glace-coque le long de la proue présente, non seulement, une méthode d'évaluer la résistance totale dans la glace, mais fournit aussi au concepteur un outil utile pour optimiser l'efficacité d'un brise-glace. Une série de 3 coques sont proposées pour illustrer qu'en maintenant une relation optimale entre les angles de la ligne d'eau et de devers, il est possible de grandement améliorer l'efficacité dans la glace, sans pour autant affecter la performance en eau libre. La résistance dans la glace prédite pour les 3 coques proposées montre une amélioration sensible par rapport au brise-glace R-Class.				
17. Mots clés Résistance de la glace uniforme Proue brise-glace Modèle mathématique		18. Diffusion Diffusion d'exemplaires en nombre limité au Centre de développement des transports		
19. Classification de sécurité (de cette publication) non classifiée	20. Classification de sécurité (de cette page) non classifiée	21. Déclassification (date)	22. Nombre de pages 87	23. Prix

ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge the financial and technical support supplied by the Transportation Development Centre and the Canadian Coast Guard.

The author is particularly indebted to Jacques Laframboise and Ian Bayly (Transportation Development Centre, Policy and Coordination Group), Paul Lacroix and Daniel Gauvin (Canadian Coast Guard), and John Carter (Kristi Maritime Inc.) for their technical and editorial suggestions.



SUMMARY

This report describes the continued research on the mathematical predictor model developed by D. Carter. In order to simplify the analyses of the complex interactions at the ship-ice interface, the formulation contains the following assumptions:

- the ship, of conventional icebreaker form, moves continuously through an uniform, level ice field of constant thickness and properties, without any internal pressure.

Full scale observations of the continuous icebreaking process show a characteristic breaking pattern. As the ship impacts the intact ice cover, local crushing and radial cracks are observed. A further increase of the load leads to more radial cracks followed by the formation of one or more rows of circumferential cracks that cause final ice cover failure.

Based on observations that an ice cover cracks radially prior to its destruction, it is concluded that the largest force that the ice cover may exert on a ship hull is the force capable of breaking up the sectorial plate formed by the radial cracks emanating from the loaded area.

A review of the relevant literature shows that there was no reliable ice failure criterion. One of the main reason for this lack of dependable methods was that most investigators had used the differential equation for a homogeneous and isotropic thin elastic plate for the formulation of the ice cover problem.

In an actual floating ice plate, the lower surface is always at the freezing temperature while the upper surface is subjected to low air temperatures. The investigators did not take into consideration that the material parameters vary across the plate thickness with the temperature profile.

In order to utilize the already available solutions, modified characteristic lengths are obtained by integrating average material properties throughout the ice thickness.

The rather complicated solution for a floating ice wedge which has been previously obtained by means of a contour integral in a complex plane is approximated with little, if any, loss of accuracy, by an empirical formula.

SUMMARY (Cont'd)

The procedures of analysis then consider the individual force created at each point of contact along the waterplane and add them up to determine the total resistance. These results are then modified to include the amplifying effect of velocity.

Noting that the idealized representation of the complex interaction at the ship-ice interface is, at best, a simplified approximation, the predicted resistance results of the math model are compared with model test results, other predictors, and full scale data. Correlation is shown to be quite good over a broad spectrum of ship form.

Sensitivity analysis is performed on major ship and ice parameters and trend results presented in graphical form to illustrate their relative significance and influence on the total ship resistance in ice. The mid-body flare angle and maximum beam are the two dominant parameters on total resistance, with forebody length and stem angle as the next most significant parameters followed by half entrance angle.

Bow form optimization on the sole basis of lower level ice resistance results in rounded or square bow forms with near 0°-stem angle and near 90°-flare angle. Unfortunately, both the open-water resistance and the seakeeping performance, especially slamming, are much poorer for such extreme shape forms than for conventional icebreaker bow forms.

However, by maintaining an optimum relationship between the waterline and flare angles along the forebody length, it is possible to obtain a shiplike design that offers a good compromise between:

- Level icebreaking performance;
- Performance in other ice conditions;
- Hydrodynamic behavior.

A computer program is developed that generates, from a set of designer-selected parameters, a preliminary lines plan that maximizes ice performance.

In order to illustrate the generation process, a series of 3 preliminary bow forms are obtained. The program output is then used, as input data, in a conventional hull lines generation program: MACSURF.

The overall lines for the three conceptual bow forms developed by R. Desgagnés are presented along with offsets tables. The predicted level ice resistance for the three proposed bow forms shows a significant improvement over the R-Class icebreaker.

SOMMAIRE

Le présent rapport décrit la recherche poursuivie sur le modèle mathématique développé par D. Carter pour prédire la résistance de navires dans la glace. Pour simplifier l'analyse de l'interaction à l'interface coque-glace, la formulation du problème fait appel aux hypothèses suivantes:

- le brise-glace, de forme conventionnelle, se déplace, en mode continu, à travers un champ de glace uniforme et homogène, d'épaisseur constante, sans contrainte interne.

Les observations en nature de la rupture de la glace en mode continu mettent en évidence un mécanisme de rupture caractéristique. Lorsque le navire heurte le champ de glace, on observe de l'écrasement local et des fissures radiales. A une augmentation de la force correspond la formation de fissures radiales additionnelles suivie de l'apparition d'une ou plusieurs rangées de fissures circonférentielles qui entraînent la rupture de la plaque de glace.

D'après les observations qu'un champ de glace se fissure en secteurs avant de se briser, on conclut que la plus grande force qu'un champ de glace peut exercer sur une coque est la force suffisante pour briser la plaque délimitée par les fissures radiales émanant de la zone de contact.

Une revue de la littérature met en évidence qu'il n'y a pas de critère fiable de rupture de la glace. Une des principales raisons de cette lacune est que la plupart des chercheurs emploient pour la formulation du problème d'un champ de glace l'équation différentielle correspondant à une plaque mince, élastique, isotrope et homogène.

Dans une plaque réelle de glace, la surface inférieure est toujours à la température de fusion alors que la surface supérieure est soumise aux températures de l'air.

Les chercheurs n'ont pas tenu compte que les paramètres du matériau variaient à travers l'épaisseur de la plaque avec le profil de température.

Pour pouvoir utiliser les solutions déjà disponibles, des longueurs caractéristiques modifiées ont été calculées en intégrant des distributions moyennes de propriétés sur l'épaisseur de la glace.

La solution, plutôt compliquée, d'un coin sur fondation élastique qui avait été obtenue préalablement au moyen d'une intégrale de contour dans un plan complexe a été approximée très justement par une formule empirique.

SOMMAIRE (Suite)

Dans la procédure d'analyse, on considère alors la force individuelle créée à chaque point de contact le long de la ligne d'eau et on les additionne pour obtenir la résistance totale. Ces résultats sont alors modifiés pour inclure l'effet amplificateur de la vitesse.

Réalisant bien que la représentation idéalisée des interactions complexes à l'interface coque-glace est, au mieux, une approximation simplifiée, les résistances calculées par le modèle sont comparées aux résultats d'essais en modèle réduit, aux autres formules et aux résultats obtenus en nature. La corrélation s'avère très bonne pour une large gamme de navires aux formes variées.

On effectue une analyse de sensibilité sur les principaux paramètres du navire et de la glace et on présente les tendances sous forme graphique pour illustrer leur importance relative et leur influence sur la résistance totale du navire dans la glace. L'angle de dévers au milieu du navire et la largeur maximale sont les 2 principaux paramètres, suivis de la longueur de la proue, de l'angle de l'étrave et du demi-angle d'attaque de la ligne d'eau.

L'optimisation de la proue sur la seule base d'une résistance moindre dans la glace uniforme résulte dans des proues cylindriques et carrées. Il est toutefois manifeste que ces formes non-profilées offrent une grande résistance en eau libre et une mauvaise tenue en mer et ne sont pas adaptées à une utilisation généralisée.

Toutefois, en maintenant une relation optimale entre l'angle de la ligne d'eau et l'angle de dévers à chaque point le long de la proue, il est possible d'obtenir une forme profilée qui offre un bon compromis entre:

- la résistance dans la glace uniforme;
- la performance dans les autres types de glace;
- le comportement hydrodynamique.

Un programme informatisé est préparé pour générer, à partir de paramètres choisis, des lignes préliminaires qui maximisent la performance dans les glaces.

Pour illustrer la procédure, une série de 3 proues préliminaires est développée. Les résultats du programme sont introduits dans un programme standard de génération de lignes de coque: MACSURF.

Les plans de lignes pour les 3 concepts de proue développés par R. Desgagnés sont fournis avec les tables de coordonnées.

Leur résistance dans la glace montre, selon les calculs, une amélioration importante par rapport au navire brise-glace "R-Class".

TABLE OF CONTENTS

	Page
INTRODUCTION	1
1.: MODE OF APPROACH AND ASSUMPTIONS	3
2.: ICE FAILURE CRITERION	13
3.: DEFINITION OF BOW GEOMETRY	21
4.: ICE RESISTANCE	27
4.1.: Ice Resistance Referred to the Stem	27
4.2.: Ice Resistance Referred to Bow Sides	29
5.: CORRELATION ANALYSIS	33
5.1.: Carter's Model Versus Model Tests	33
5.2.: Carter's Model Versus Other Predictors ..	42
5.3.: Carter's Model Versus Full Scale Data ...	46
5.4.: Comments from Users	50
6.: INFLUENCE OF SHIP AND ICE PARAMETERS	51
7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE	58
7.1.: Design Waterline and Waterline Angles ...	58
7.2.: Flare Angle Distribution along Forebody :	60
7.3.: Conceptual Bow Forms	65
8.: PRACTICAL APPLICATIONS.....	81
8.1.: "DCARTER" Program.....	81
8.2.: "WAAS" Program.....	81
8.3.: "OPTIBOW" Program.....	81
8.4.: "NEWBOW" Program.....	81
CONCLUSIONS.....	82
REFERENCES.....	84

LIST OF FIGURES

	Page
Figure 1.1.: Idealized Ice Breaking Pattern ..	4
Figure 1.2.: Typical Load-Time Curves	7
Figure 1.3.: Generalized Load-Time Curve for Ice	9
Figure 1.4.: Attenuation of Ice Cover Deflection, z , and Wave Elevation, w , with distance from bow	11
Figure 2.1.: Characteristic Length for Various Types of Ice Cover	14
Figure 2.2.: Schematic Representation of a Floating Truncated Wedge whose Free Edge is subjected to an Oblique Load	16
Figure 2.3.: Comparison of Proposed Formula with USSR Design Standards and Rules for Loads exerted by Ice on Hydraulic Structures	18
Figure 2.4.: Comparison between Ice Crushing Force and Buckling load	20
Figure 3.1.: Definition of Coordinate Systems and Bow Angles	22
Figure 3.2.: Geometrical Parameters as interpolated by a Cubic Spline Curve :	24
Figure 3.3.: Bow Lines Approximated by an Arc of an Ellipse	26
Figure 4.1.: Characteristics of the Ice-Stem Interface and Force Diagram	28
Figure 4.2.: Characteristics of the Hull-Ice Interface and Force Diagram	30
Figure 4.3.: Influence of the Number of Elementary Contact Areas	32

LIST OF FIGURES (Cont'd)

	Page
Figure 5.1.: CCGS LOUIS S.ST.LAURENT - Comparison between Full Scale Regression Equations, Model Test Results and Predictions by Math Model	35
Figure 5.2.: R-CLASS ICEBREAKER - Comparison between Full Scale Regression Equations, Model Test Results and Predictions by Math Model	37
Figure 5.3.: Comparison between Full Scale Data, Model Test Results and Predictions by Carter's Math Model	39
Figure 5.4.: M.V. ARCTIC (Original Bow) - Comparison between Full Scale Regression Equations, Model Test Results and Predictions by Math Model	41
Figure 5.5.: CCGS LOUIS S. ST.LAURENT - Comparison between Full Scale Regression Equation, and Predic- tions by Math Model and Other Predictors	43
Figure 5.6.: R-CLASS ICEBREAKER - Comparison between Full Scale Regression Equations, and Predictions by Math Model and Other Predictors..	44
Figure 5.7.: M.V. ARCTIC (Original Bow) - Comparison between Full Scale Regression Equations, and Pre- dictions by Math Model and Other Predictors	45
Figure 5.8.: LOUIS S. ST.LAURENT - Comparison Between Ice Resistance Measure- ments, and Predictions by Pro- posed Math Model	47

LIST OF FIGURES (Cont'd)

	Page
Figure 5.9.: VLADIVOSTOK - Comparison between Ice Resistance Measurements, and Predictions by Proposed Math Model	48
Figure 5.10.: JELPPARI - Comparison between Ice Resistance Measurements, and Predictions by Proposed Math Model :	49
Figure 6.1.: Geometrical Parameters of the Candidate Ship as Computed by the Elliptical Function	52
Figure 6.2.: Influence of a) Maximum Beam and b) Ratio "Forebody Length/Maximum Beam" on Ice Resistance	53
Figure 6.3.: Influence of a) Half-Entrance Angle and b) Mid-Body Flare Angle on Ice Resistance	54
Figure 6.4.: Influence of a) Stem Inclination with Horizontal and b) Friction Coefficient on Ice Resistance ...	55
Figure 6.5.: Influence of a) Ice Flexural Strength and b) Ice Thickness on Ice Resistance	56
Figure 7.1.: Comparison of R-Class Design Waterline and Waterline Angles with Bow Branch and Waterline Angles Defined by the Elliptical Function	59
Figure 7.2.: Analytical Distribution of Flare Angles along the Bow Section as a Function of the Exponent "N"	60
Figure 7.3.: Comparison of Analytical Distributions of Flare Angles along Forebody Length with Actual R-Class Distribution	61
Figure 7.4.: Influence of the Distribution of Flare Angles along the Forebody Length on Ice Resistance	62

LIST OF FIGURES (Cont'd)

	Page
Figure 7.5.: Effects of Modifying Half-Entrance Angle, Mid-ship Flare Angle, and Flare Angle Distribution along Forebody Length	63
Figure 7.6.: Predicted Level Ice Resistance for R-Class Icebreaker and the 3 Proposed Bow Forms	64
Figure 7.7.: Designer-Controlled Ship Parameters in the Program "OPTIBOW"	66
Figure 7.8.: Unfair Forebody Plan;Exponent=1,0:	68
Figure 7.9.: Unfair Forebody Plan;Exponent=1,5:	69
Figure 7.10.: Unfair Forebody Plan;Exponent=2,0:	70
Figure 7.11.: Lines Plan;Conceptual Bow Form "A" Exponent=1,0	73
Figure 7.12.: Lines Plan;Conceptual Bow Form "B" Exponent=1,5	75
Figure 7.13.: Lines Plan;Conceptual Bow Form "C" Exponent=2,0	77



INTRODUCTION

This study of icebreaking resistance has been supported by Transportation Development Centre (TDC) during the past eight years. The objective, as originally stated, was to explore the possibility of deriving, on purely analytical grounds, a relatively simple model, sensitive to both hull characteristics and environmental conditions, which could:

- 1.: predict ship resistance to continuous motion through level ice;
- 2.: provide a better understanding of the complex interactions at the ship-ice interface.

In 1983, through a series of assumptions and simplifications, Carter (1983) proposed a totally new analytical approach to the resistance of sheet ice to the motion of a ship. When applied to a broad spectrum of ship types, the correlation of results was found to be quite good, and certainly better than all previous empirically derived relationships. (Milano 1983).

Facing a lack of reliable methods for predicting the largest forces an ice plate can exert on a ship's hull, it was then decided to devote considerable effort to derive a rigorous ice failure criterion based on both theory and experiments. (Carter 1986).

Considering the promising results obtained previously by the use of the new approach taken, it then appeared worth developing an enhanced version of the original model to solve the icebreaking resistance without the use of unjustified assumptions and simplifications. A computer program "ICEBREAK" was developed that facilitated problem solution and allowed for systematic variation of ice and ship parameters. This program, along with interpolation routines to determine the hull offsets, can predict the normal and the frictional components of the icebreaking force at any point along the hull-ice interface. (Carter 1987). The force distribution along the hull of an icebreaker, as predicted by the Carter's model, has recently been verified and validated by the use of a segmented physical model. (Glen et al. 1989).

INTRODUCTION (Cont'd)

Extensively tested by many independent users, the math model has demonstrated its ability to accurately predict level ice resistance for a wide spectrum of bow forms under extreme operating conditions.

Following discussions with the sponsor, TDC, it was planned to use the program, as a design tool, to generate an optimal bow form for icebreaking.

This document gives an overview of the whole project with an emphasis on its last phase, the bow form optimization for level ice performance.

Essentially, the report will be subdivided as follows:

- 1.: Mode of Approach and Assumptions;
- 2.: Ice Failure Criterion;
- 3.: Bow Geometry Definition;
- 4.: Level Ice Resistance;
- 5.: Correlation Analysis;
- 6.: Influence of Ship and Ice Parameters; and
- 7.: Bow Form Optimization.

1.: MODE OF APPROACH AND ASSUMPTIONS

The interactions which occur at the ship-ice interface in breaking and moving through ice fields are so complex that they will probably elude for ever an exact mathematical formulation. It may be noted that it has not yet been possible to explain the resistance encountered by a ship in open water by means of one universal expression.

Moreover, Mother Nature is least cooperative; she seldom provides us with a constant-thickness, uniform ice field, free of cracks, thermal stress, and internal pressure. Depending on the hydrodynamic and meteorological conditions at the freezing moment, there is almost an infinite variety of ice types formed over rivers, lakes, and northern seas. The mechanical/physical ice properties are highly variable, in time and space, and seldom known with an accuracy greater than 20%.

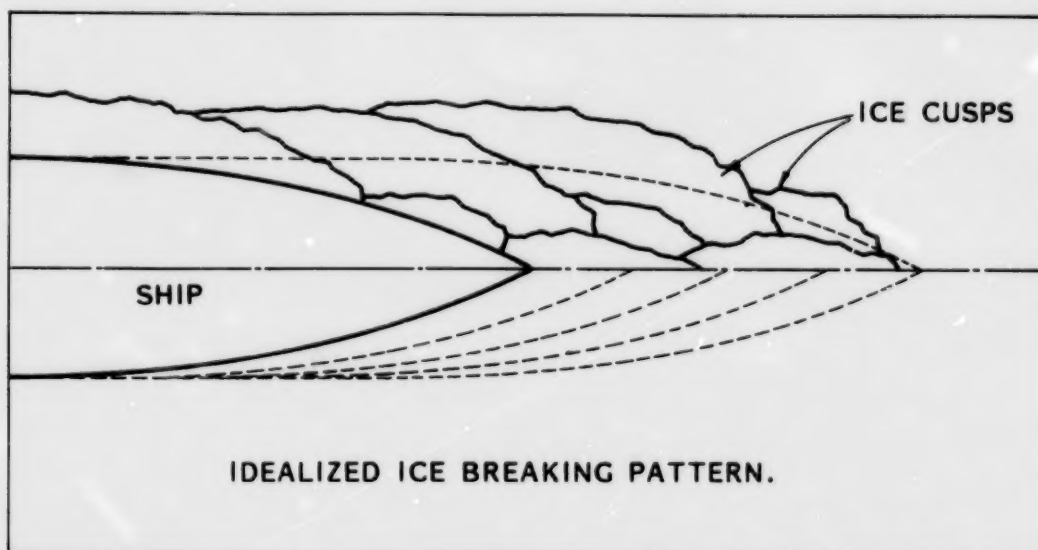
In view of the variation of ice properties in an actual ice cover and its effect upon ship resistance, it appears sufficient to utilize a formulation of the hull-ice interaction based on a certain number of simplifying assumptions. However, it is essential that the assumptions made be justified from a physical point of view, and that the validity of the formulation be substantiated by relevant results of laboratory and field tests.

In order to simplify the problem of ship resistance to continuous motion in ice, it is assumed throughout this analysis that:

the ship, of conventional icebreaker form, moves continuously (as opposed to ramming) through an uniform, level ice field of constant thickness and properties, without any internal pressure.

Full-scale observations of the continuous icebreaking process shows a characteristic breaking pattern. As the ship impacts the intact ice cover, local crushing and radial cracks are observed. A further increase of the load leads to more radial cracks followed by the formation of one or more rows of circumferential cracks at which time the sectorial plates formed by the radial cracks collapse.

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)



As the ship impacts the unbroken pack, local crushing is observed. As loading of the ice continues, series of radial cracks appear followed by one or more rows of circumferential cracks just prior to ice failure.

FIGURE 1.1

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)

The wedges as they fail tend to give rise to a series of cusps and associated cusp points which themselves become load points as the ship moves forward while pushing aside, upturning, or submerging the broken ice pieces. The repetitive breaking cycle is completed as the ship again impacts with the unbroken pack, at the line of ice fracture.

To date, most analytical treatment has been based on ship motion equations during a typical breaking cycle and has considered either energy balance (Milano, 1973) or conservation of momentum (Naegle, 1980).

Contrary to this usual approach, our analysis will be stated from the point of view of the ice cover. The ice resistance to ship motion is simply set equal to the average force sufficient to keep the ice cover breaking for the given set of geometrical and material parameters.

The problem will be addressed in two steps: First, expressions will be developed for the ship-ice interaction under a quasi-static condition, which takes account of ship parameters, ice characteristics and friction. These results will then be modified to include the amplifying effects of velocity by introducing the effect of the upward pressure of the bow wave under the ice.

The resistance of a ship moving continuously through a level ice sheet is made of several components. There are elastic forces, inertial forces, dynamic forces, friction forces, and gravity forces, all acting simultaneously.

Following Kashteljan et al. (1968), most researchers represent the total icebreaking resistance, R_t , by an equation of the following basic form:

$$R_t = R_b + R_s + R_v + R_w$$

R_b is the resistance associated with breaking ice;
 R_s is associated with turning and submerging ice;
 R_v is associated with ship's velocity;
 R_w is the open-water resistance.

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)

thereby expressing resistance due to ice forces, R_i , in three terms:

$$R_i = R_t - R_w = R_b + R_s + R_v$$

In May 1983, Enkvist (1983) presented the results of model and full-scale tests conducted, at creeping speed, ($R_v = 0$), to determine the relative magnitude of the breaking and submerging components of resistance. The basic conclusion of this work was:

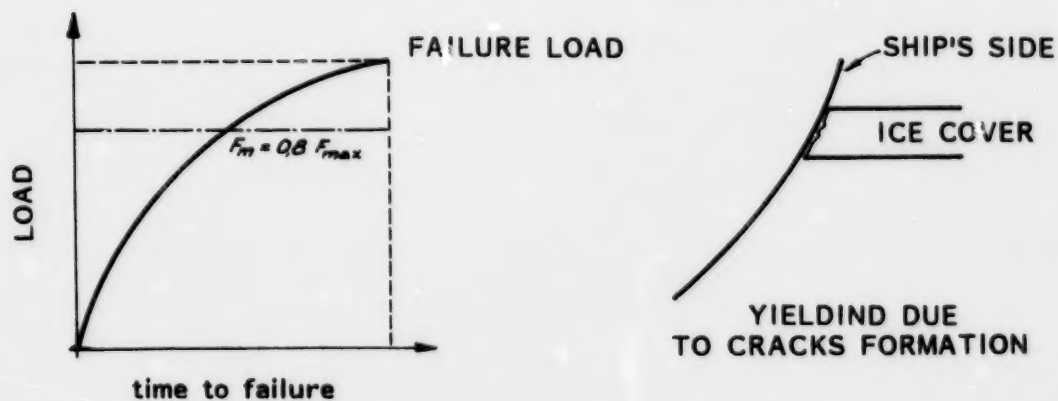
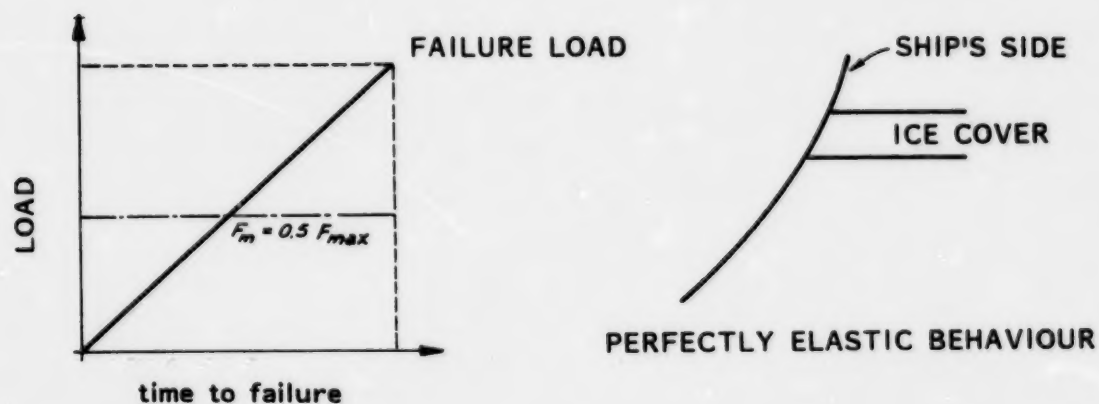
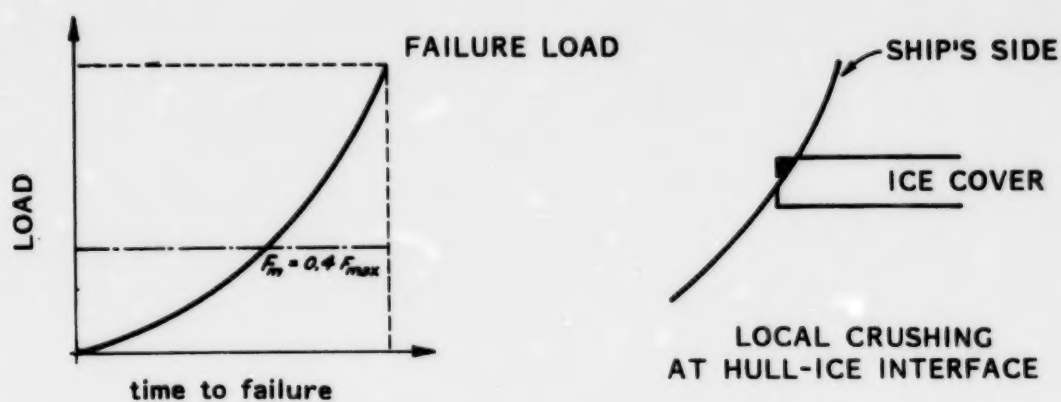
the breaking component of resistance varies between 40 and 80% of total resistance at very low speeds.

$$R_b = 0.4 \text{ to } 0.8 (R_b + R_s)$$

which is consistent with the findings of Poznyak and Ionov (1981) and Vance (1975).

Each individual breaking force acting at various locations along the bow-ice interface is oscillatory in nature; varying from zero at the instant of first contact to failure load as the ice cover breaks. For perfectly elastic behaviour, the load-time curve is linear and the breaking force averaged on the loading interval corresponds to 50% of the failure load. But nonlinear load-time curves are also common. For small contact points, the ice is first crushed till the crushed area is sufficiently large to carry the applied force which then increases proportionally to ice cover deformation. On the other hand, micro-cracks are sometimes formed inside the loaded ice cover thus allowing a certain yielding before final failure. Considering the highly variable load histories, from zero to failure load, it seems reasonable to assume that the average breaking resistance, which is the summation of all the individual components acting at various locations along the waterplane, may also vary between:

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)



TYPICAL LOAD-TIME CURVES

FIGURE 1.2

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)

$$R_b = 0.4 \text{ to } 0.8 (R_{\max})$$

where $R_{\max}$ is the maximum thrust that the ice cover may exert against the ship's bow.

From the two above equations, we obtain:

$$R_b + R_s = R_{\max}$$

Due to the brittle nature of ice, there is never a complete contact between an impinging structure and an ice sheet. Normally, the ice sheet makes contact over many small areas, and the coefficient allowing for incomplete simultaneous contact with ice over whole area was extensively studied by Korzhavin (1971) who obtained a mean value of 0.6, now universally accepted for computing maximum ice thrust on structures.

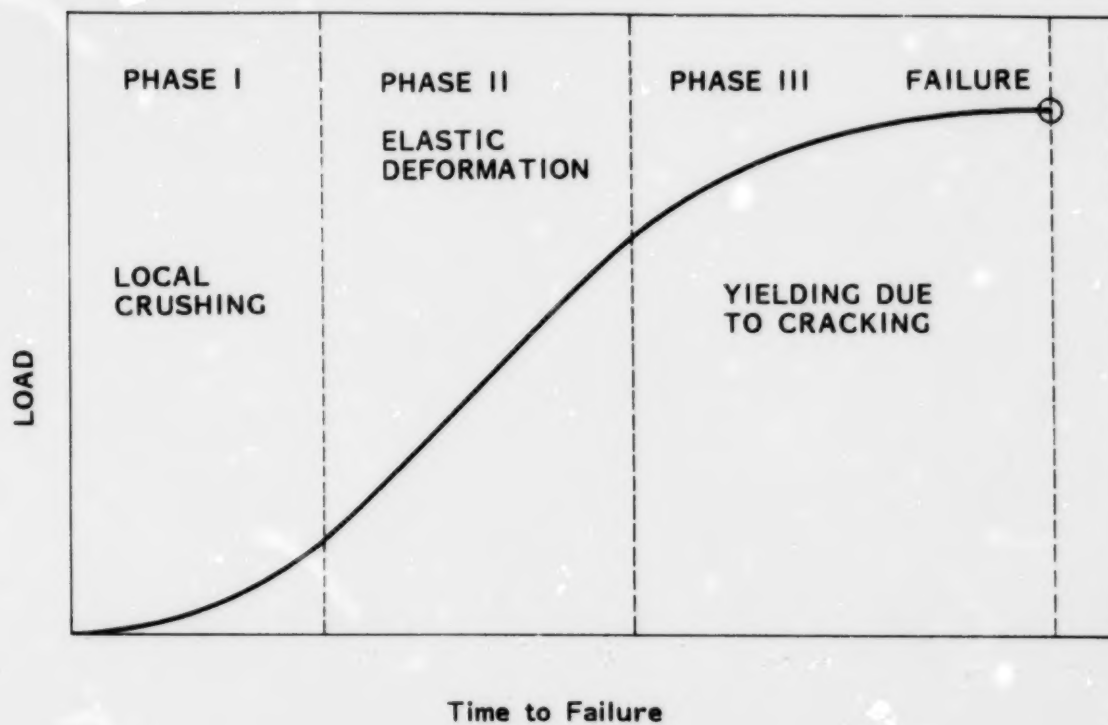
Therefore, the above equation may be rewritten as:

$$R_b + R_s = R_{\max} = 0,6 R_{\text{full}}$$

where R_{full} is the ice thrust predicted for a full contact at the hull-ice interface.

The velocity resistance will be obtained by introducing the effect of the upward pressure of the bow wave under the ice. The peculiar system of waves which accompanies a ship moving through deep water is a very complex matter. However, as shown by Everest and Hogben (1969), it is possible to deduce from the two-dimensional solution obtained by Lamb (1932) an approximation to the water surface shape which may be adequate for many practical purposes.

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)



GENERALIZED LOAD-TIME CURVE FOR ICE

Depending on the relative importance of each phase, the average load for the loading interval may vary between about 40 to 80% of the FAILURE LOAD.

FIGURE 1.3

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)

Since, in the vicinity of the bow, both the ice cover deflection, z , as calculated by Nevel's theory (1961) and the transient wave elevation, w , as obtained by Lamb (1932) show a similar rapid attenuation as the distance from the bow increases, it may be assumed that:

$$w = z (w(0)/z(0))$$

The effect of adding the uplifting head due to bow wave is equivalent to increasing the foundation modulus, γ .

$$p = z\gamma + w\gamma$$

$$p = z\gamma (1 + w/z)$$

$$p = z\gamma (1 + w(0)/z(0))$$

$$p = z\gamma'$$

where

$$\gamma' = \gamma (1 + w(0)/z(0))$$

where $z(0)$, the ice cover deflection at the ship contact is obtained from Nevel's theory as:

$$z(0) = 0.04 \frac{\sigma h^2}{\ell^2}$$

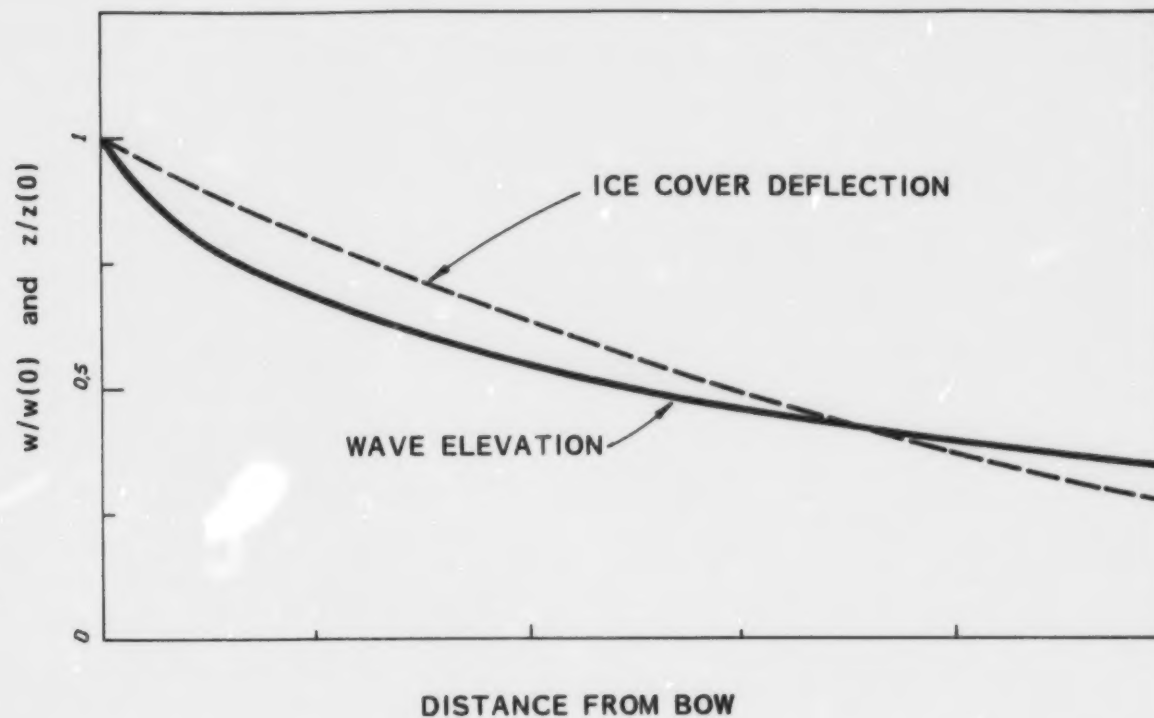
σ : ice flexural strength (kPa) ; h : ice thickness (m);
 ℓ : ice plate characteristic length (m).

For lack of better information, the wave elevation at the bow, $w(0)$, was estimated, for the low icebreaking speeds, from the data summarized by Sorensen (1973) for a wide variety of ship forms:

$$w(0) = 0.016 V^2$$

V being the ship's speed (m/s).

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)



ATTENUATION OF ICE COVER DEFLECTION, z , AND WAVE ELEVATION, w , WITH INCREASING DISTANCE FROM BOW.

FIGURE 1.4

1.: MODE OF APPROACH AND ASSUMPTIONS (Cont'd)

Noting that:

- 1.: Under both static and dynamic conditions, the elastic ice cover deflection must be equal to induce an internal stress equal to the ice flexural strength;
- 2.: According to Nevel's theory, the force, P , required to produce a certain deflection is proportional to the square root of the foundation modulus.

we may write:

$$P_{\text{dyn.}} = k \gamma'^{\frac{1}{2}}$$

$$P_{\text{sta.}} = k \gamma^{\frac{1}{2}}$$

k being a constant of proportionality.

The two above equations allows us to write:

$$P_{\text{dyn.}} = P_{\text{sta.}} (\gamma' / \gamma)^{\frac{1}{2}}$$

Thence, the total ice resistance, including the velocity component, must be increased by the following factor:

$$R_i = 0,6 R_{\text{full}} \left[1 + \frac{0.4V^2 \ell^2}{\sigma h^2} \right]^{\frac{1}{2}}$$

It is very convenient to divide R_{full} , the failure load corresponding to a full contact at the hull-ice interface, into two (2) components:

$$R_i = 0,6 (R_1 + R_2) \left[1 + \frac{0.4V^2 \ell^2}{\sigma h^2} \right]^{\frac{1}{2}}$$

where R_1 is the ice thrust acting at the stem and R_2 is the summation of all individual ice thrusts acting along the bow sides.

2.: ICE FAILURE CRITERION

A review of the relevant literature up to 1982 had evidenced that there was no reliable analytical method for predicting the largest forces an ice cover might exert on a ship's hull.

One of the main reasons for this lack of dependable methods was that most investigators had utilized an ice failure criterion obtained by assuming a homogeneous thin elastic plate.

In actual floating ice plates, the temperature varies across the plate thickness, from freezing point at the lower surface to air temperature at the upper surface. Since the ice mechanical properties, mainly the elastic modulus, vary drastically with small changes of temperature near 0°C, the material parameters vary strongly across the thickness of the plate; hence, the floating ice plate is inhomogeneous and the usual homogeneity assumption is not justified from a physical point of view.

However, Kerr and Palmer (1972) have proved that all solutions obtained in the literature for a homogeneous plate are applicable to floating ice plate problems if, and only if, the "characteristic length" which reflects the flexural rigidity of the plate is evaluated by integrating the actual material properties throughout the ice thickness.

Assuming, for temperature and salinity, average profiles observed under natural conditions, Carter (1986) has obtained the characteristic length, ℓ , of a floating ice sheet as:

$$\ell = 0,75 \ell^*$$

where ℓ^* is the characteristic length of a homogeneous elastic plate defined by:

$$\ell^* = \left[\frac{E h^3}{12 \gamma (1 - \nu^2)} \right]^{\frac{1}{4}}$$

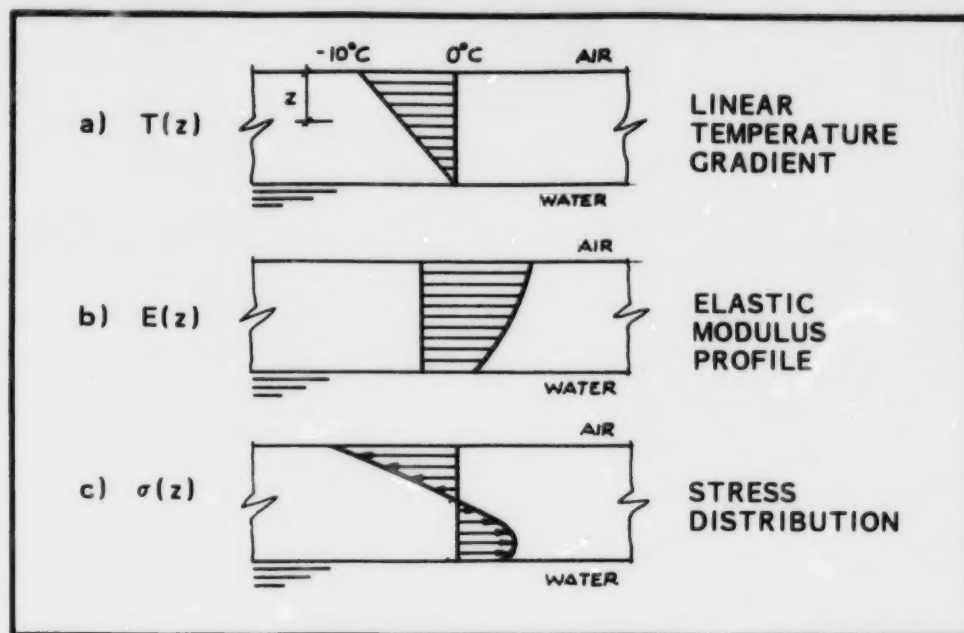
where E : elastic modulus (kPa);

h : ice thickness (m);

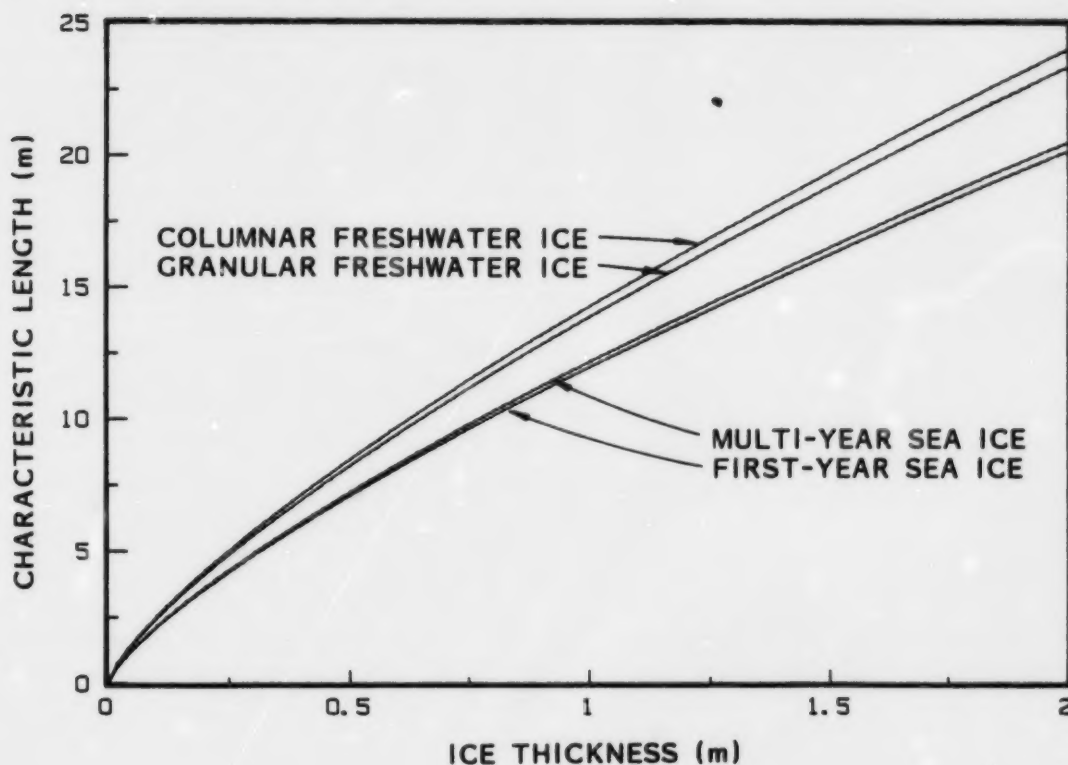
γ : unit weight of the underlying water (kN/m³);

ν : Poisson's ratio.

2.: ICE FAILURE CRITERION (Cont'd)



STRESS DISTRIBUTION (c), AND ELASTIC MODULUS PROFILE (b) IN AN ICE PLATE FOR A LINEAR TEMPERATURE GRADIENT (a).



CHARACTERISTIC LENGTH FOR VARIOUS TYPES OF ICE COVERS.

2.: ICE FAILURE CRITERION (Cont'd)

Introducing typical values into the above equations, the following results were obtained:

$$l = 14,3 \text{ h}^{\frac{1}{3}} \quad \text{for columnar fresh water ice;}$$

$$l = 13,9 \text{ h}^{\frac{1}{3}} \quad \text{for granular fresh water ice;}$$

$$l = 12,0 \text{ h}^{\frac{1}{3}} \quad \text{for first-year sea ice;}$$

$$l = 12,2 \text{ h}^{\frac{1}{3}} \quad \text{for multi-year sea ice.}$$

These relations, theoretically derived by Carter (1986), have been confirmed by Gold (1988) who observed that, for elastic conditions, the characteristic length of fresh water ice cover is in the range of 12,6 to 15,0 $\text{h}^{\frac{1}{3}}$.

By taking into consideration the variation of material parameters with depth, the characteristic length is reduced by a factor of 75%. This correction implies that the predicted buckling load which is, as we will see later, proportional to l^3 will be reduced by a factor of 42%.

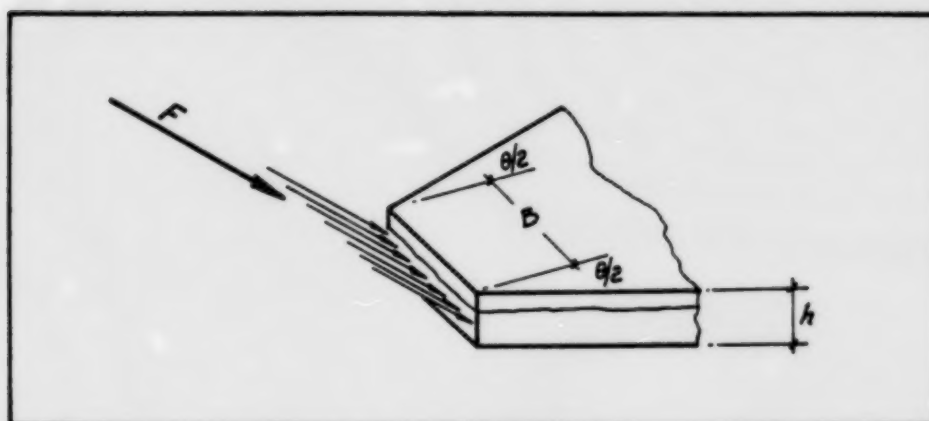
Field observations show that ice cover failure occurs in two stages. First, at a certain intensity of load, radial cracks emanate from the loaded region. A further increase of the load leads to more radial cracks, and finally to the formation of circumferential cracks immediately followed by a break-down of the ice field.

Based on observations that an ice cover cracks radially prior to its destruction, the ice failure criterion is therefore related to the load sufficient to break the sectorial ice plates formed by the radial cracks. The occurrence of the first radial cracks does not cause breakthrough.

2.: ICE FAILURE CRITERION (Cont'd)



CHARACTERISTIC BREAKING PATTERN AS A SHIP
MOVES THROUGH AN ICE FIELD.



SCHEMATIC REPRESENTATION OF A FLOATING TRUNCATED WEDGE
WHOSE FREE EDGE IS SUBJECTED TO AN OBLIQUE LOAD.

FIGURE 2.2

2.: ICE FAILURE CRITERION (Cont'd)

Nevel (1979) has analyzed the response of floating ice wedges under the influence of both horizontal and vertical forces, i.e. oblique loads, and has obtained the exact solution by means of a contour integral in a complex plane. His solution is rather complicated and too lengthy to be reproduced here and the reader is referred to the original paper for full details.

Carter (1986) has shown that Nevel's results may be predicted with little, if any, loss of accuracy by the following much simpler empirical formula:

$$F = \frac{V}{\sqrt{\sin^2 \phi + \frac{V^2}{H^2} \cos^2 \phi}}$$

where F is the collapse force acting against the edge of an ice sheet at an angle ϕ with the horizontal.

The vertical failure load, V , is defined by:

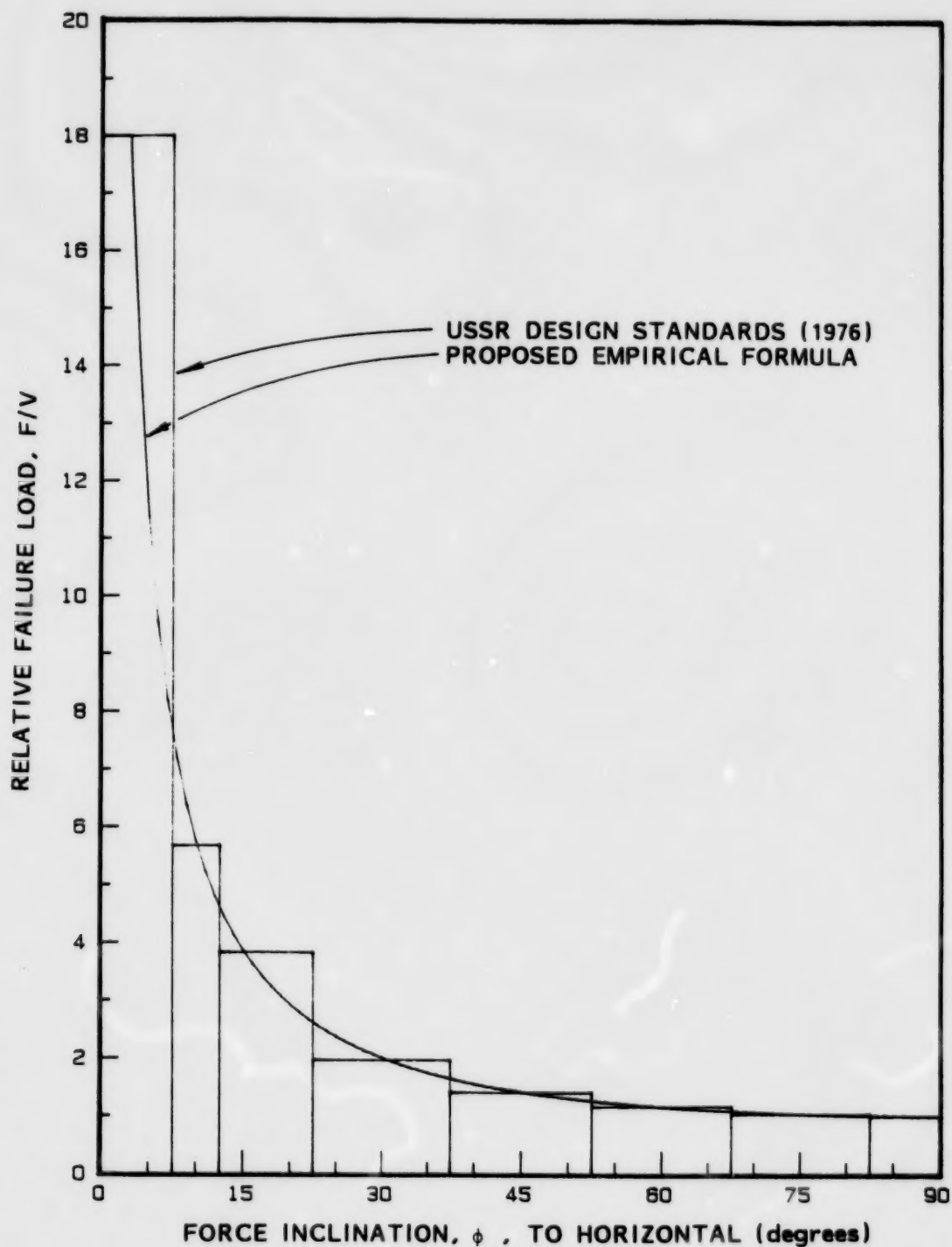
$$V = 0,38 \left(\tan \theta/2 + B/\ell \right) \sigma h^2$$

The horizontal buckling load, H , is defined by:

$$H = \left(\theta + B/\ell \right) \gamma \ell^3$$

- θ : wedge apex angle expressed in radians;
- B : width of the contact region (m);
- ℓ : characteristic length of the ice plate (m);
- σ : ice flexural strength (kPa);
- h : ice thickness (m);
- γ : unit weight of the underlying water (kN/m);

2.: ICE FAILURE CRITERION (Cont'd)



COMPARISON OF PROPOSED FORMULA WITH USSR DESIGN STANDARDS AND RULES FOR LOADS EXERTED BY ICE ON HYDRAULIC STRUCTURES (1976). These guidelines are based on extensive experimental measurements.

FIGURE 2.3

2.: ICE FAILURE CRITERION (Cont'd)

Since both crushing and buckling are possible modes of failure for an ice sheet as it impinges on an almost vertical structure, one has to check which is the easiest mode of failure when ϕ is close to 0° .

When crushing or splitting occurs prior to the buckling of the ice sheet, the horizontal component cannot be larger than the crushing load obtained by Prandtl (1920) for a truncated wedge uniformly loaded on its blunted face, which implies:

$$F \leq \frac{(1 + \theta/2) \sigma_1 B h}{\cos \phi}$$

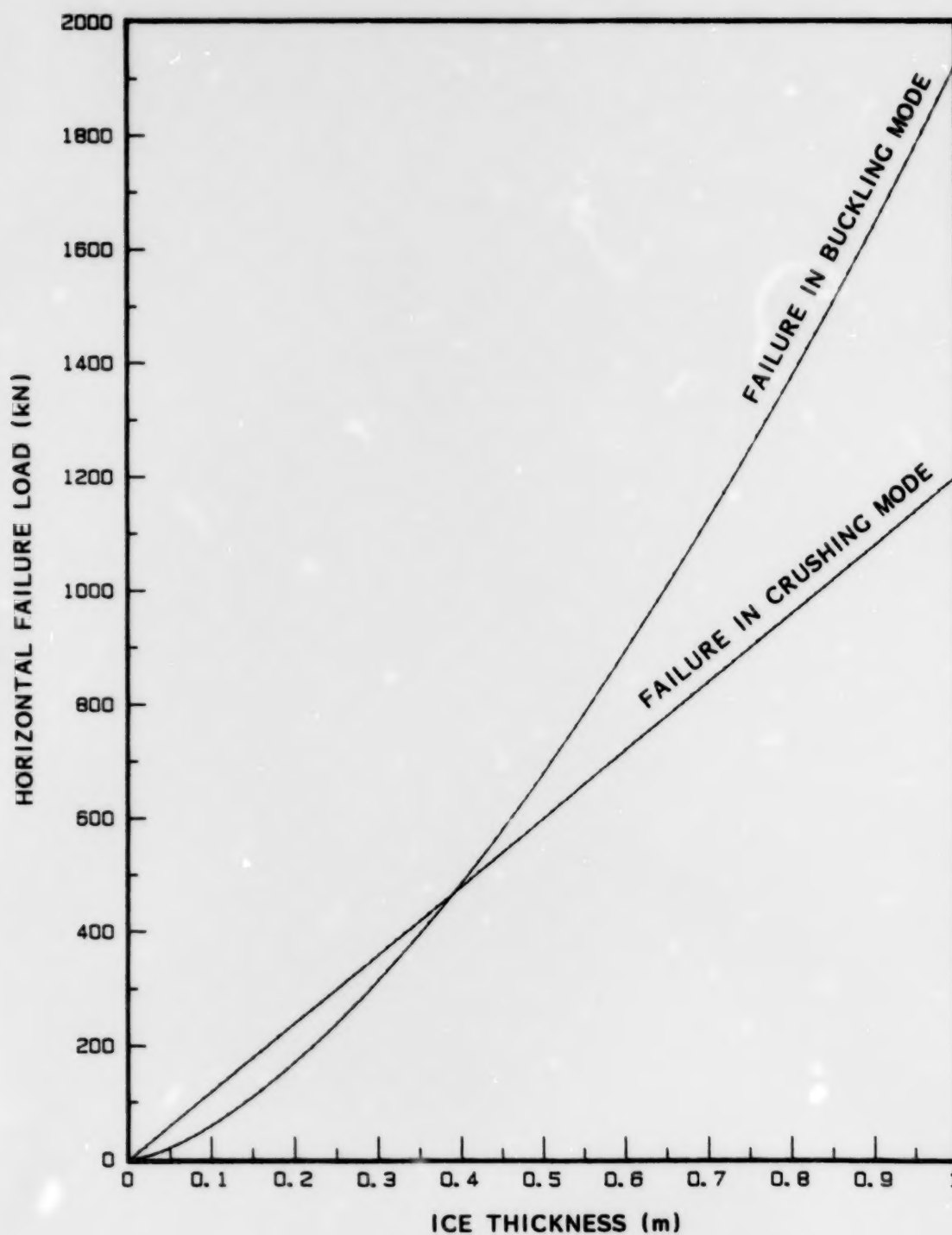
where σ_1 is the compressive strength of ice (kPa).

The maximum horizontal ice force is related to the force sufficient to fail the ice sheet in either the crushing mode or the buckling mode whichever occurs first at a lower applied load. Since the buckling load increases with $l^3 \propto h^{2.5}$ and the crushing load with h , it is obvious that an increase in the ice thickness will favor the transition from buckling to crushing.

The proposed criterion is in agreement with the observations made by Rose (1947, p. 883) who stated that 'buckling of an ice sheet does occur but that there is a limiting thickness of about 1 foot [0,3 m] beyond which buckling will rarely occur.' He also claimed that 'for very thick ice sheets (about 2 feet [0,6 m] or more) the crushing strength is the limiting factor.'

A very important conclusion is that the failure mode will be different in full scale trials and model tests for the ice plates pressing against almost vertical ship's shoulders. The actual crushing loads may be dangerously underestimated by scaling up the buckling loads measured in model tests. Normally, icebreakers with vertical sides appear more efficient in ice resistance model tests than they will be under full scale conditions.

2.: ICE FAILURE CRITERION (Cont'd)



COMPARISON BETWEEN ICE CRUSHING FORCE AND BUCKLING LOAD (B=1 m).

For $h < 0.3$ m, buckling occurs first;

For $h > 0.5$ m, crushing occurs fir

FIGURE 2.4

3.: DEFINITION OF BOW GEOMETRY

The geometry of the bow at the specific points of load application is required to create a fine breakdown of forces associated with the icebreaking phenomena. The bow form geometry is generally defined by the X-Y-Z coordinates and three (3) sets of angles: α , the waterline angle; β , the frame flare angle; γ , the buttock line angle.

From few offsets and angles measured from the lines plan, the geometrical parameters are interpolated by the use of "cubic spline functions". These interpolating functions are viewed as the smoothest of all possible curves through a given set of points. Since we use a cubic function, a minimum of four (4) points is required for each geometrical parameters and generally 7 are sufficient to properly define the bow form.

The ice forces acting at any location along the bow line, during icebreaking, are more readily resolved in their vertical, transverse, and longitudinal components, i.e. in the X, Y, and Z directions, if use is made of the three following calculable angles:

r : angle in the waterplane between direction of ship motion and perpendicular to waterline;

$$r = (90^\circ - \alpha)$$

s : angle between normal to shell plating and waterplane;

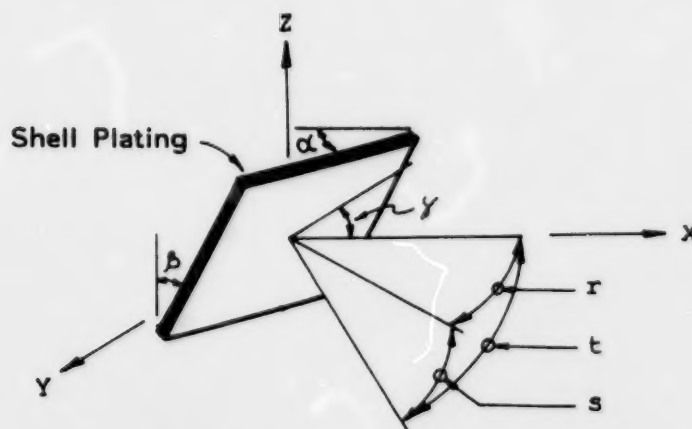
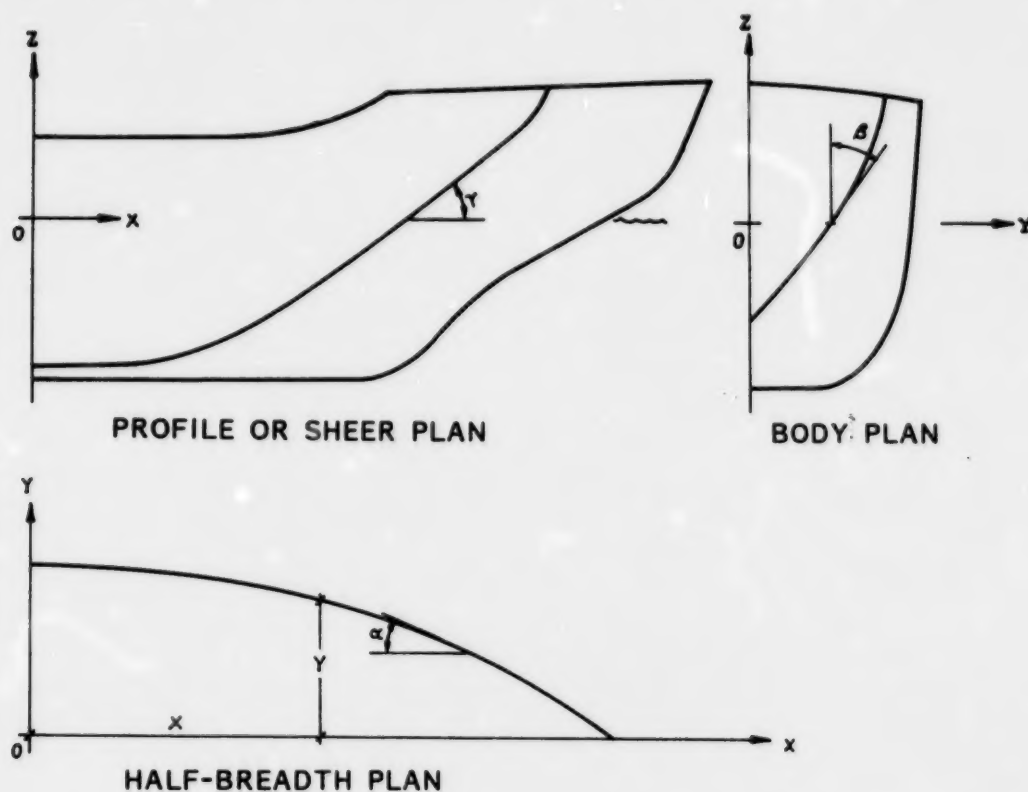
$$s = \tan^{-1}(\tan\beta \cos\alpha)$$

t : angle between direction of ship motion and normal to shell plating;

$$t = \cos^{-1}(\cos r \cos s)$$

where α and β are respectively the local waterline and flare angles.

3.: DEFINITION OF BOW GEOMETRY (Cont'd)



x : distance forward of datum taken at maximum beam;
 y : half-breadth at point x ;
 α : waterline angle;
 β : frame flare angle;
 γ : buttock angle.

DEFINITION OF COORDINATE SYSTEMS AND BOW ANGLES.

FIGURE 3.1

3.: DEFINITION OF BOW GEOMETRY (Cont'd)

CUBIC SPLINE FUNCTION

INPUT DATA

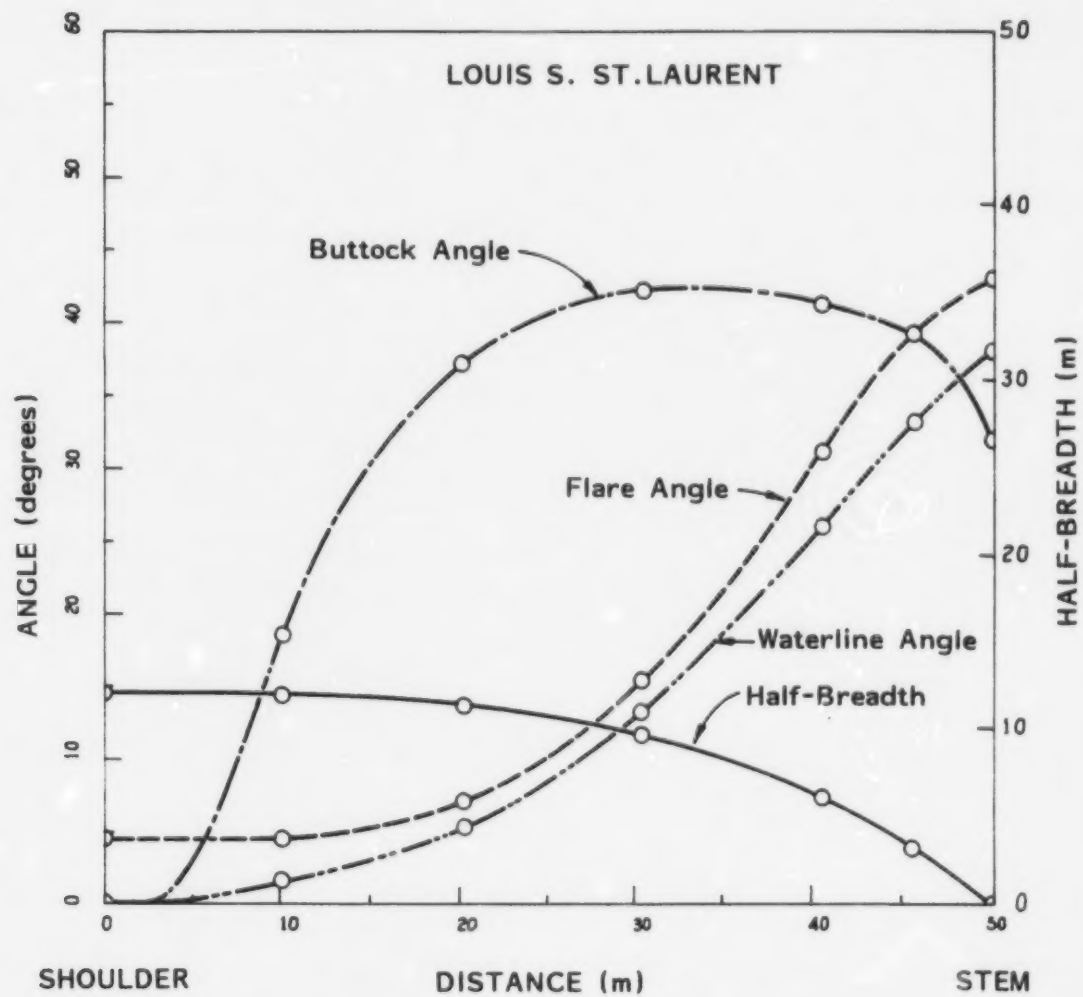
x (m)	y (m)	α (°)	β (°)	γ (°)
0.00	12.13	0.00	4.50	0.00
10.18	12.08	1.50	4.50	18.40
20.36	11.53	5.20	7.10	36.20
30.54	9.87	13.30	15.40	42.30
40.72	6.14	26.00	31.20	41.30
45.81	3.20	33.20	39.50	38.60
50.17	0.07	38.00	43.00	32.00

OUTPUT DATA

x (m)	y (m)	α (°)	β (°)	γ (°)	r (°)	s (°)	t (°)
0.00	12.13	0.00	4.50	0.00	90.00	4.50	90.00
1.00	12.13	0.00	4.51	0.00	90.00	4.51	90.00
2.00	12.13	0.00	4.52	0.00	90.00	4.52	90.00
3.00	12.13	0.02	4.52	0.04	89.98	4.52	89.98
4.00	12.13	0.08	4.52	0.84	89.92	4.52	89.92
5.00	12.13	0.19	4.50	2.33	89.81	4.50	89.81
6.00	12.13	0.35	4.48	4.61	89.65	4.48	89.65
7.00	12.12	0.57	4.45	7.54	89.43	4.45	89.43
8.00	12.11	0.83	4.43	10.87	89.17	4.43	89.17
9.00	12.10	1.13	4.44	14.37	88.87	4.44	88.88
10.00	12.08	1.44	4.49	17.81	88.56	4.49	88.56
11.00	12.06	1.77	4.58	20.95	88.23	4.58	88.23
12.00	12.03	2.11	4.72	23.75	87.89	4.72	87.90
13.00	11.99	2.45	4.90	26.22	87.55	4.90	87.56
14.00	11.95	2.78	5.11	28.35	87.22	5.10	87.23
.....							
.....							
.....							
40.00	6.49	25.00	29.79	41.49	65.00	27.42	67.96
41.00	6.00	26.40	31.75	41.22	63.60	29.00	67.11
42.00	5.50	27.90	33.71	40.90	62.10	30.53	66.23
43.00	4.95	29.41	35.55	40.45	60.59	31.90	65.36
44.00	4.37	30.84	37.14	39.82	59.16	33.04	64.55
45.00	3.74	32.18	38.51	39.11	57.82	33.96	63.78
46.00	3.07	33.43	39.72	38.50	56.57	34.74	63.08
47.00	2.36	34.60	40.81	37.99	55.40	35.40	62.43
48.00	1.63	35.72	41.73	37.05	54.28	35.91	61.78
49.00	0.91	36.78	42.41	35.15	53.22	36.19	61.10
50.00	0.19	37.82	42.92	32.48	52.18	36.30	60.38

TABLE 3.1

3.: DEFINITION OF BOW GEOMETRY (Cont'd)



GEOMETRICAL PARAMETERS AS INTERPOLATED BY A CUBIC
SPLINE FUNCTION.

FIGURE 3.2

3.: DEFINITION OF BOW GEOMETRY (Cont'd)

When only principal particulars, i.e. maximum beam, B ; forebody length (from max. beam to stem), L' ; half entrance angle, α ; stem angle, γ ; and midbody flare angle, β ; are known and extreme accuracy is not deemed essential, the bow branch of conventional icebreakers may be approximated by an arc of an ellipse.

$$y = \frac{B}{2} - b \left[1 - \left(1 - \frac{x^2}{a^2} \right)^{\frac{1}{2}} \right]$$

$$\text{with } a = \left[\frac{L'^2}{1 - \frac{(b - B/2)^2}{b^2}} \right]^{\frac{1}{2}}$$

$$b = \frac{B (2 mL - B)}{4 (mL - B)}$$

$$m = \tan \alpha$$

The waterline angle is given by:

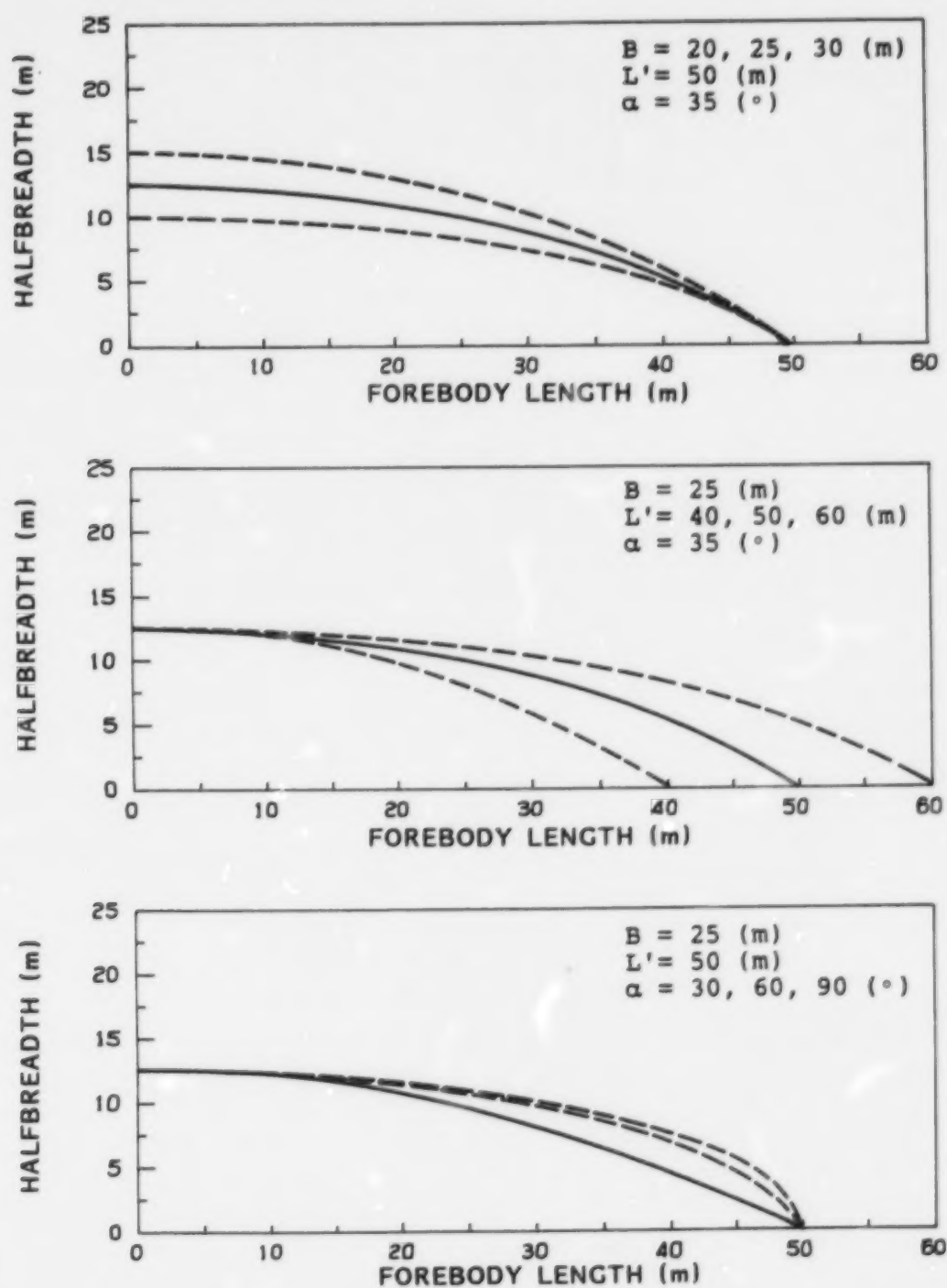
$$\tan \alpha(x) = \frac{b^2}{a^2} \frac{x}{(y + b - B/2)}$$

The flare angles and the buttock angles are then determined by superimposing, at $z = z + \Delta z$, a new elliptical arc satisfying the conditions corresponding to the frame flare angle at the maximum beam section and the stem angle. We then obtain for any point along the bow lines:

$$\beta(x) = \tan^{-1} \Delta y / \Delta z$$

$$\gamma(x) = \tan^{-1} \Delta z / \Delta x$$

3.: DEFINITION OF BOW GEOMETRY (Cont'd)



BOW LINES APPROXIMATED BY AN ARC OF AN ELLIPSE.

FIGURE 3.3

4.: ICE RESISTANCE

4.1: ICE RESISTANCE REFERRED TO THE STEM

Based on observations that the first cracks to form in an unbroken ice sheet emanate radially from the loaded area, normally to the free edge, we will consider, for the determination of R_1 , the failure load of the sectorial plate defined by two radial cracks perpendicular to the waterline in the immediate vicinity of the stem.

At the stem, during the breaking process, ice slides along the buttock lines. It follows from direction cosine mathematics shown by Runeberg (1889) that the direction of application, ϕ , of the resultant force is given by:

$$\phi = \tan^{-1} \frac{\sin \alpha \cos \gamma - f \sin \gamma}{\sin \alpha \sin \gamma + f \cos \gamma}$$

Using the previous ice failure criterion, the critical load, F_1 , making an angle, ϕ , with the horizontal is:

$$F_1 = \frac{V^2}{\sqrt{\sin^2 \phi + \frac{V^2}{H^2} \cos^2 \phi}}$$

where V , the vertical failure load, and H , the horizontal buckling load are, for $\theta = \pi - 2\alpha$ and $B = 0$, given by:

$$V = 0,38 \cot \alpha \sigma h^2$$

$$H = (\pi - 2\alpha) \rho \ell^3$$

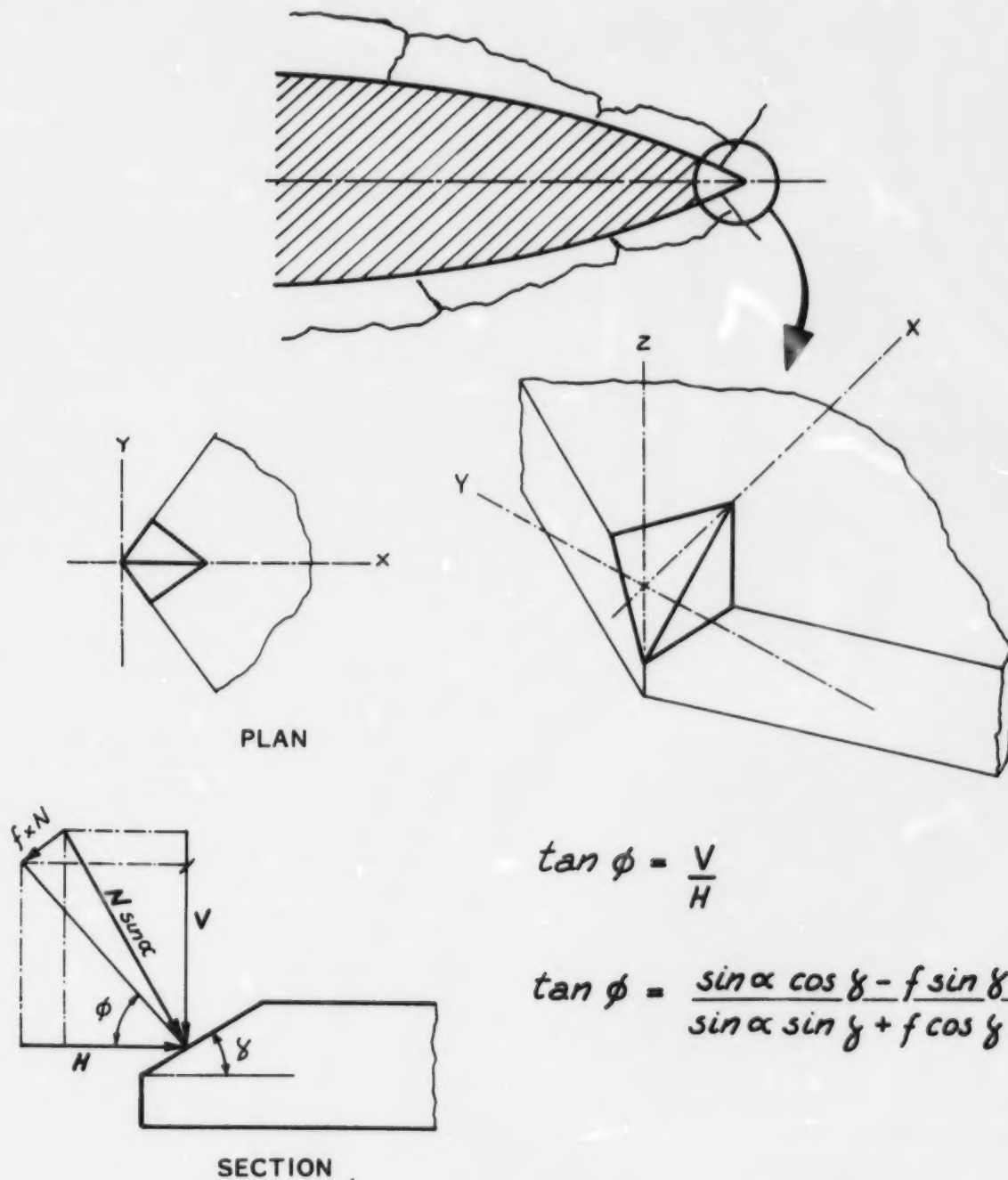
where ρ is the unit weight of the underlying water and α , the half entrance waterline angle is expressed in radians.

The resistance referred to the stem, R_1 , is then directly obtained as:

$$R_1 = F_1 \cos \phi$$

4.: ICE RESISTANCE

4.1: ICE RESISTANCE REFERRED TO THE STEM (Cont'd)



CHARACTERISTICS OF THE ICE-STEM INTERFACE AND FORCE DIAGRAM.

FIGURE 4.1

4.: ICE RESISTANCE

4.2: ICE RESISTANCE REFERRED TO BOW SIDES

To determine the total resistance referred to the sides, R_2 , the hull-ice interface is first discretized into "n" elementary contact areas. No effect is considered aft of the maximum beam since relief occurs there and any force due to ice-ship interaction is relieved.

At each contact point, the applied load may always be resolved into normal and tangential components. The direction of the friction force is necessarily in the direction of the relative motion between the two friction surfaces.

The direction of relative motion prior to ice cover failure is determined, for any point along the bow branch, from the two (2) following considerations:

- 1.: The relative motion takes place in a plane tangent to the hull-ice interface;
- 2.: The relative motion is in the same plane as its inducing forces: a component of thrust in OX-direction and a reaction force normal to shell plating.

These two (2) conditions are simultaneously satisfied only along the intersection line of the plane tangent to hull-ice interface with the plane defined by the normal to shell plating and OX-direction.

Thus, the direction of friction is, at the stem, along the buttock lines, then varies gradually to become, at mid-body, in the direction of the waterlines.

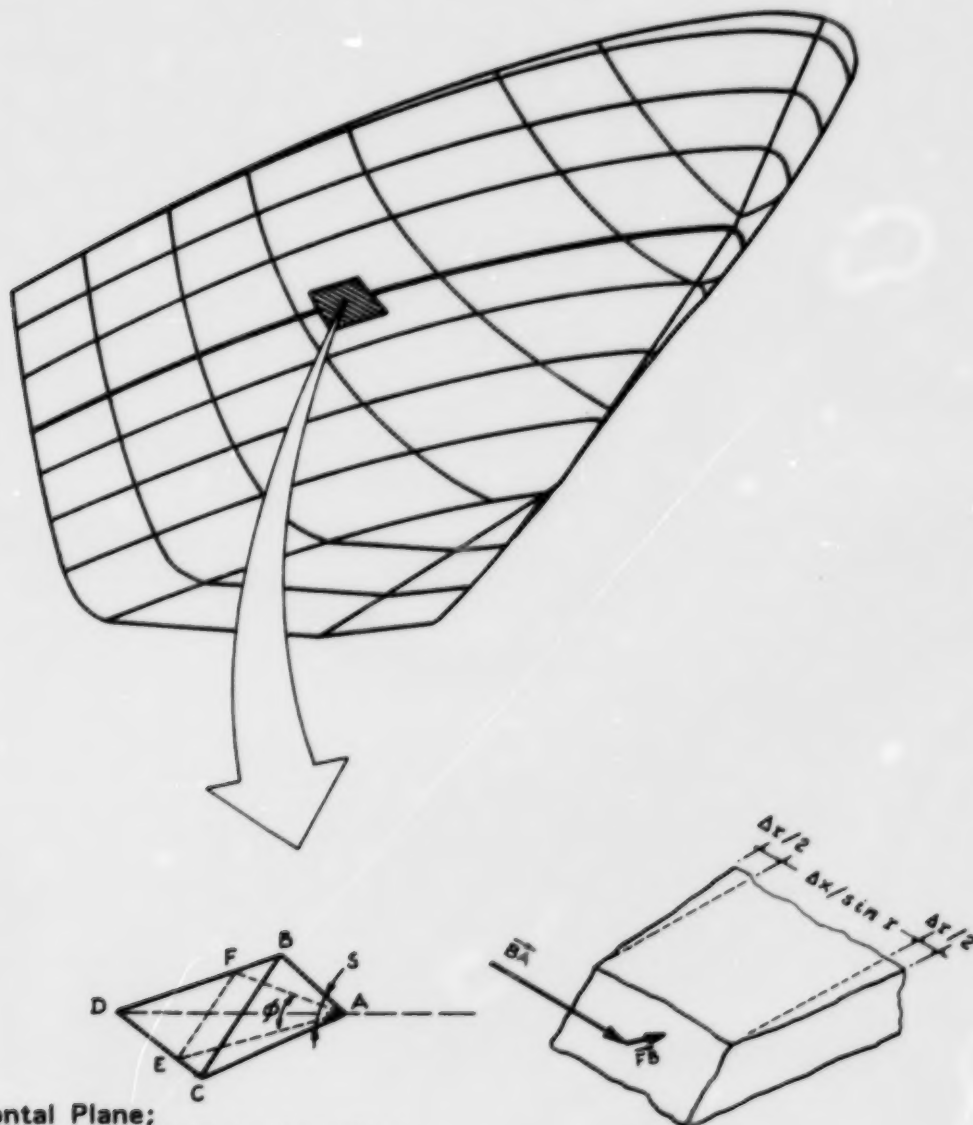
From trigonometrical considerations, the direction of application, ϕ , of the resultant force on each elementary contact area is obtained as:

$$\phi = \tan^{-1} \tan s \frac{\sin(t - f')}{\sin t}$$

where $f' = \tan^{-1} f$; f being the friction coefficient.

4.: ICE RESISTANCE

4.2: ICE RESISTANCE REFERRED TO BOW SIDES (Cont'd)



- DAC : Horizontal Plane;
 DBC : Plane tangent to hull-ice interface
 DBA : Plane defined by the direction of ship motion
 and the normal to hull-ice interface.

$$\tan \phi = \frac{EF}{FA} = \tan s \left(\frac{\sin(t-f)}{\sin t} \right)$$

CHARACTERISTICS OF THE HULL-ICE INTERFACE AND
FORCE DIAGRAM.

FIGURE 4.2

4.: ICE RESISTANCE

4.2: ICE RESISTANCE REFERRED TO BOW SIDES (Cont'd)

The direction of application, ϕ , being known, the critical load required to break the truncated wedge acting against the elementary bow length is readily obtained from the failure criterion:

$$\Delta F_2 = \frac{V}{\sqrt{\sin^2 \phi + \frac{V^2}{H^2} \cos^2 \phi}}$$

with

$$V = 0,38 (\tan(\Delta r/2) + \Delta a/\ell) \sigma h^2$$

and

$$H = (\Delta r + \Delta a/\ell) \rho \ell^3 \quad ; \quad \Delta a = \sqrt{\Delta x^2 + \Delta y^2}$$

However, since crushing is also a possible mode of failure, the horizontal component of the oblique force cannot be larger than the crushing load given by:

$$\Delta F_2 \leq \frac{1 + \Delta r}{\cos \phi} \Delta a \sigma_1 h$$

where σ_1 is the ice compressive strength.

The elementary contribution to R_2 is then:

$$\Delta R_2 = \Delta F_2 \cos(t - f')$$

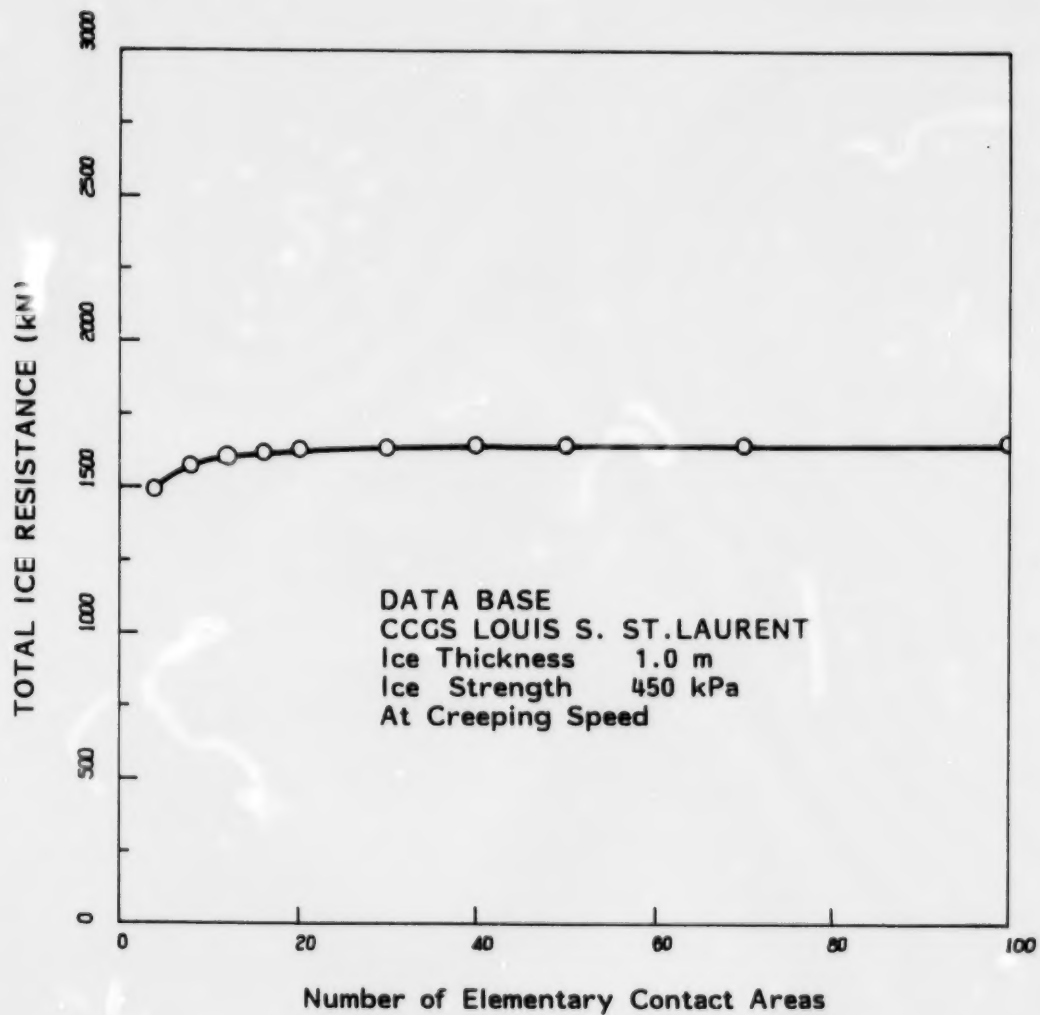
Assuming the ice forces symmetrical about OX, the total resistance referred to the sides is then obtained as:

$$R_2 = 2 \sum_{i=1}^n \Delta R_2$$

where "n" is the number of subintervals considered on each side of the bow. To insure convergence of the numerical integration, the forebody section is subdivided into 50 elementary contact areas.

4.: ICE RESISTANCE

4.2: ICE RESISTANCE REFERRED TO BOW SIDES (Cont'd)



INFLUENCE OF THE NUMBER OF ELEMENTARY CONTACT AREAS.

FIGURE 4.3

5.: CORRELATION ANALYSIS

Noting that the idealized representation of the complex interactions at the hull-ice interface during ice breaking is, at best, a simplified approximation, it is essential that the validity of the proposed model be confirmed by relevant laboratory and field tests.

In order to establish its predictive ability, we shall compare the predicted resistance results of the proposed math model against:

- 1.: Model test results;
- 2.: Other predictors;
- 3.: Full scale data.

5.1.: CARTER'S MODEL VERSUS MODEL TESTS

For realistic comparative assessment of the predictive capability of the math model versus model test results, full scale data are required to act as the benchmark against which the predictions could be compared. The M.V. ARCTIC (original bow), R-CLASS Icebreaker, and LOUIS S. ST. LAURENT were selected for this comparative purpose because:

- 1.: They were probably the three most extensively model tested ships;
- 2.: Full scale data on their ice performance was readily available from literature;
- 3.: They represented a broad spectrum of ship hull configurations.

For each candidate ship, the full scale data will be plotted as a benchmark against which both the math model predictions and the model test results will be compared graphically. In all our math model runs, the friction coefficient between hull and ice will be set to the most commonly used value of 0.1.

5.: CORRELATION ANALYSIS
5.1.: CARTER'S MODEL VERSUS MODEL TESTS
5.1.1: LOUIS S. ST. LAURENT

Level ice resistance tests were carried out on CCGS LOUIS S. ST. LAURENT under two extremely dissimilar ice conditions. Data obtained during trials, in 1970, were collected using the method of ramming into a solid 1,0 m ice sheet containing about 50% of multi-year ice. The regression equation for the 1970 set of data points is, for $h=1,0$ m and $\sigma=600$ kPa: (Edwards et Alt. 1976)

$$R = 1014 h^2 + 1,22 h \sigma + 683 V h^{3/2}$$

The data obtained from trials in 1979 and 1980, were acquired in weak melting one-year ice. The regression equation for the 1979 and 1980 sets of data points is, for $h=1,0$ m and $\sigma=125$ kPa: (Lewis et Alt. 1982)

$$R = 422 h^2 + 1,22 h \sigma + 340 V h$$

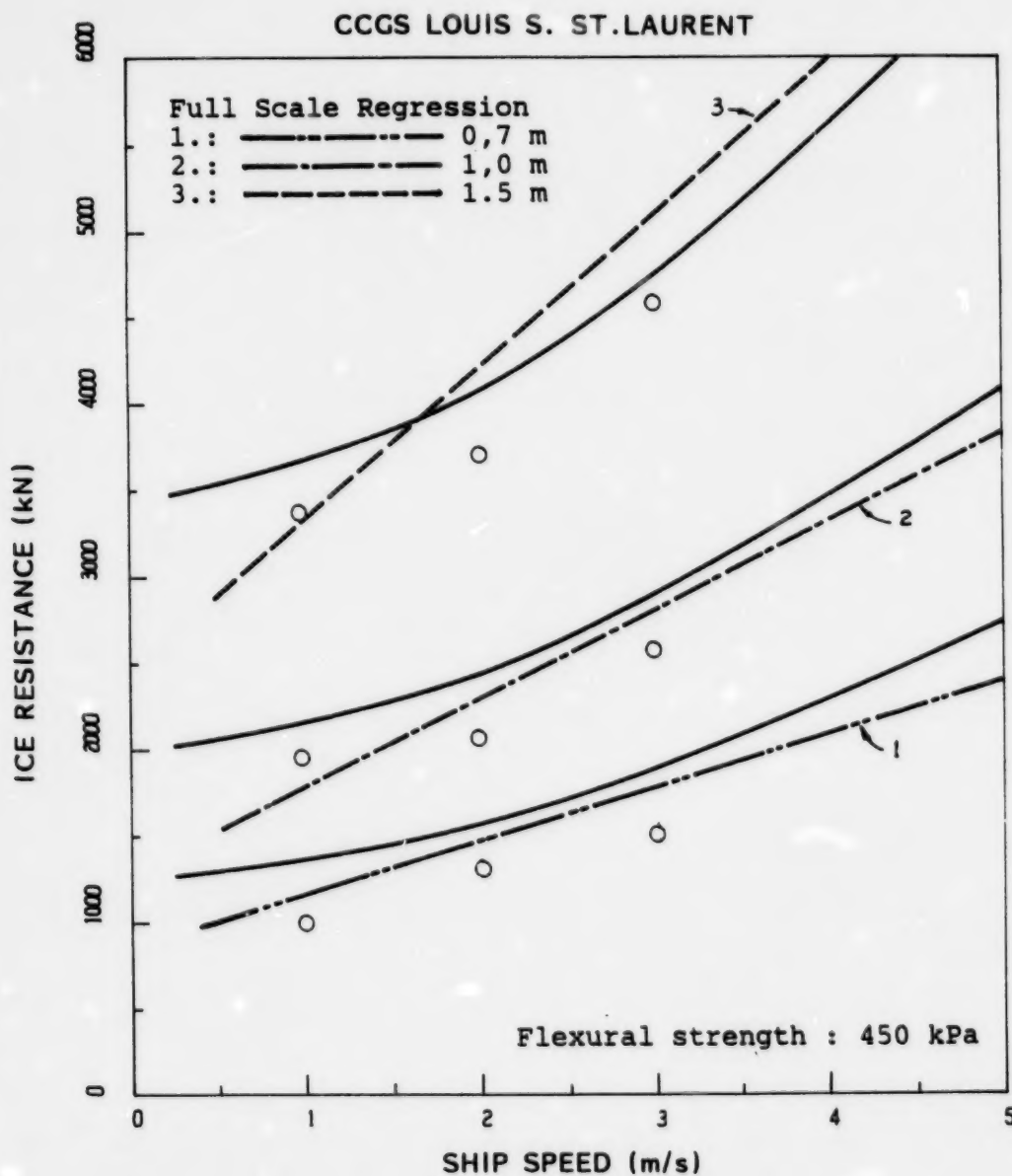
For our comparative purposes, we will use, as a reference line for full scale data in normal ice, the average of the two above equations:

$$R = 718 h^2 + 1,22 h \sigma + 341 V h^{3/2} + 170 V h$$

in which R is in kN; h in m; σ in kPa; and V in m/s.

In the series of studies and tests commissioned by the Canadian Coast Guard for the LOUIS mid-life modernization, the Institute for Marine Dynamics has tested the original bow at $\sigma=450$ kPa full scale, at three ice thicknesses over a range of ship speeds (Spencer 1987). These model test results scaled-up using the Froude's system are used for comparison with math model results and the regression equations for the full scale data points.

5.: CORRELATION ANALYSIS
 5.1.: CARTER'S MODEL VERSUS MODEL TESTS
 5.1.1: LOUIS S. ST. LAURENT (Cont'd)



COMPARISON BETWEEN FULL SCALE REGRESSION EQUATIONS,
 MODEL TEST RESULTS AND PREDICTIONS BY MATH MODEL.

FIGURE 5.1

5.: CORRELATION ANALYSIS
 5.1.: CARTER'S MODEL VERSUS MODEL TESTS
 5.1.2: R-CLASS ICEBREAKER

FULL SCALE DATA

Field trials were carried out with two R-Class Ice-breakers operated by the Canadian Coast Guard. In February 1979, extensive trials were conducted aboard CCGS Radisson in 0,25 to 0,8 m of winter fresh and saline ice with $\sigma=475$ kPa (Edwards et Alt. 1981). In the winter of 1979-80, full scale trials were also carried out with CCGS Franklin in Lake Melville (Michailidis and Murdey 1981). During the two Franklin probes, the ice thicknesses were respectively 0,7 and 0,8 m, $\sigma=475$ kPa, and $E/\sigma=8000$. For our comparison purposes, we will use as a benchmark the full scale data points for $h=0,8$ m the only ice thickness common to both sets of measurements.

MODEL TEST RESULTS

In 1981, the International Towing Tank Conference, (ITTC), developed a model test program for the most recent Canadian R-Class icebreaker. Each of the four participating organizations, CRREL, WADM, AARI, and HSVA, have tested the R-Class model at the 0,7 m full scale thickness, at varying ice strengths over a range of ship speeds. The model results were gathered by Dr. R.V. Milano and subjected to linear regression analysis. The resulting trend lines for $h=0,7$ m and $\sigma=475$ kPa are as obtained by Milano (1983):

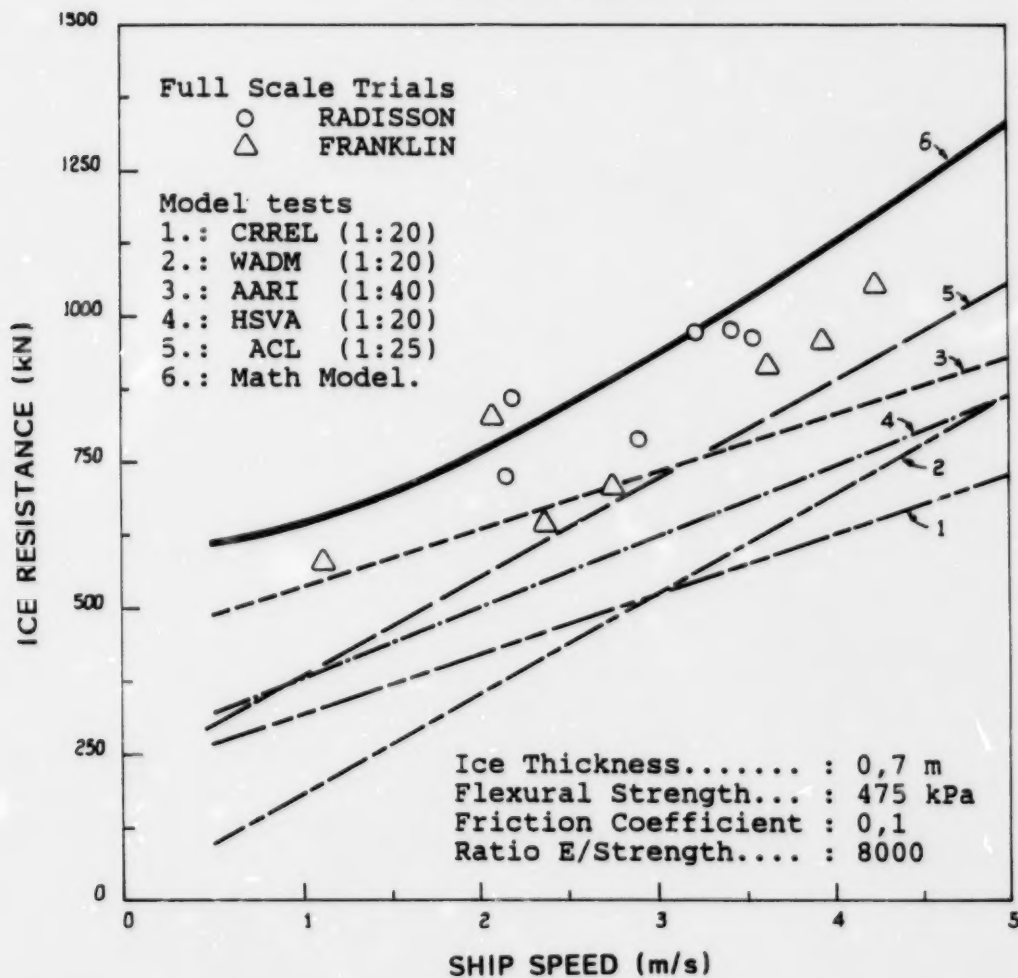
$R = 217 + 102 V$	CRREL (1:20)
$R = 11,4 + 170 V$	WADM (1:20)
$R = 438 + 98 V$	AARI (1:40)
$R = 259 + 121 V$	HSVA (1:20)

The trend line obtained by ARCTEC in 1979 for the R-Class under the considered conditions was:

$R = 217 + 168 V$	ACL (1:25)
-------------------	------------

5.: CORRELATION ANALYSIS
 5.1.: CARTER'S MODEL VERSUS MODEL TESTS
 5.1.2: R-CLASS ICEBREAKER (Cont'd)

R-CLASS ICEBREAKER



COMPARISON BETWEEN FULL SCALE REGRESSION EQUATIONS,
 MODEL TEST RESULTS AND PREDICTIONS BY MATH MODEL.

FIGURE 5.2

5.: CORRELATION ANALYSIS
5.1.: CARTER'S MODEL VERSUS MODEL TESTS
5.1.2: R-CLASS ICEBREAKER (Cont'd)

SEGMENTED MODEL TESTS

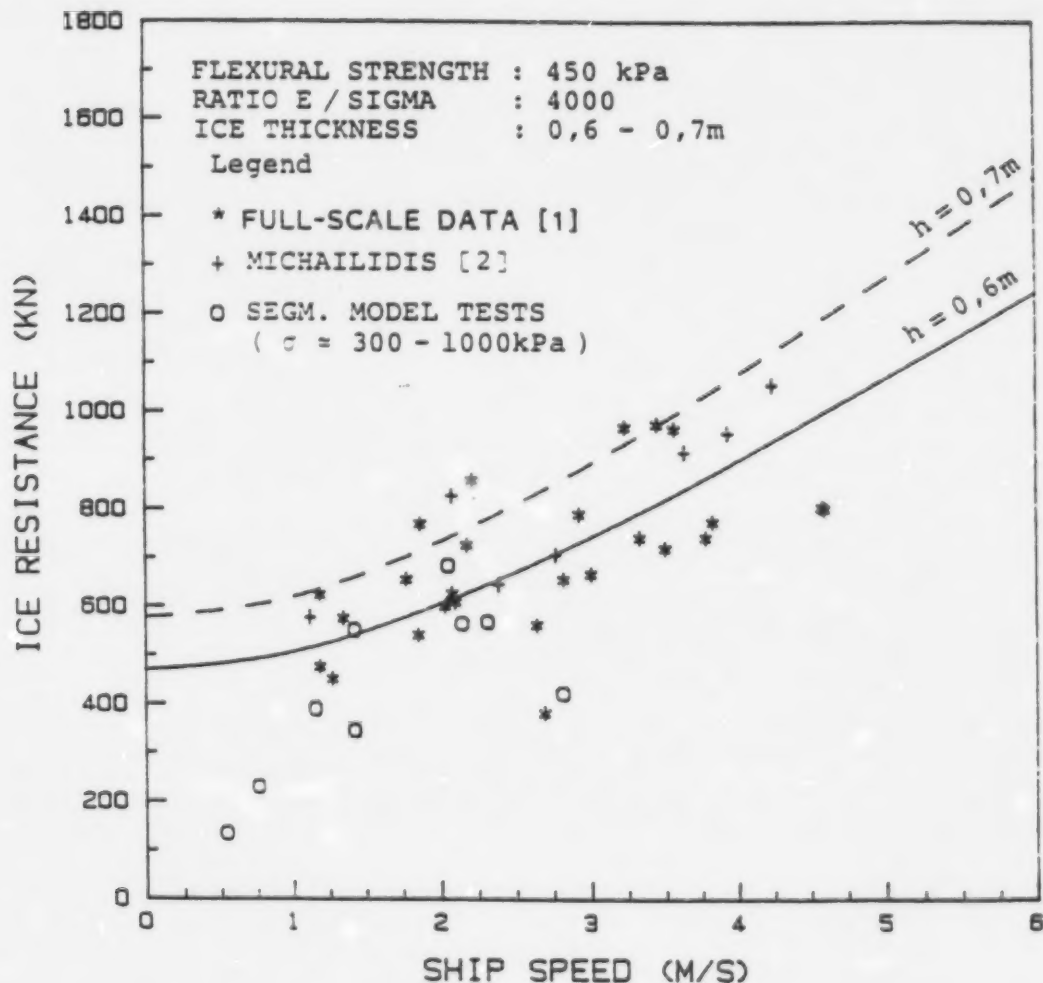
In 1989, an experimental program designed to investigate the components of ice resistance on the hull of a vessel using a physically segmented model has been completed by FLEET TECHNOLOGY Ltd (Glen et Al. 1989). The objective was to compare the loads measured on portions of the hull with those predicted by mathematical prediction models, with a view to obtaining a greater understanding of the ship/ice interaction process.

The data have been analyzed to investigate the local ship/ice interaction phenomena and to determine the contribution to resistance from each portion of the hull. The results have been compared with the proposed math model.

It is concluded that the relative contributions of resistance of the portions of the hull agree well with Carter's model: (page 113)

"Carter's model correlates well with the full scale data for this specific vessel (CCGS RADISSON), and there is reason to suppose that the math model predicts well the force distribution along the hull and recognizes the changes in the dynamic load histories. This is underscored by the good correlation between mean values of measured and calculated contributions. The model experimental evidence suggests that there may be high normal loading aft on the bow as is predicted by the Carter's model."

5.: CORRELATION ANALYSIS
 5.1.: CARTER'S MODEL VERSUS MODEL TESTS
 5.1.2: R-CLASS ICEBREAKER (Cont'd)



Reproduced from:

Glen, I.F., Abdelnour, R., Steele, M., 1989, Modification and Testing of a Segmented Model of an Icebreaker to Evaluate Ice Resistance Mathematical Models. TP 9849E, Report Prepared for Transportation Development Centre by Fleet Technology Limited, March 1989.

FIGURE 5.3

5.: CORRELATION ANALYSIS
5.1.: CARTER'S MODEL VERSUS MODEL TESTS
5.1.2:M.V. ARCTIC (Original Bow)

FULL SCALE DATA

Limited full scale data for the M.V. Arctic with its original bow is available from three sets of measurements: the Lake Melville trials, the Baffin Island trials, and the Saguenay River trials. These full scale measurements were analyzed using different regression techniques and three equations were put forward as best representative of the full scale ice resistance, for $h=0,8$ m and $\sigma=500$ kPa.

$$R = 980 + 331 V \quad (\text{Lewis et Alt. 1982})$$

$$R = 1200 + 208 V + 3,342 V^{2,5} \quad (\text{Albery et Alt. 1984})$$

$$R = 1083 + 115 V + 3,342 V^{2,5} \quad (\text{Baker,D.,1984})$$

in which R is expressed in kN, and V in m/s.

MODEL TEST RESULTS

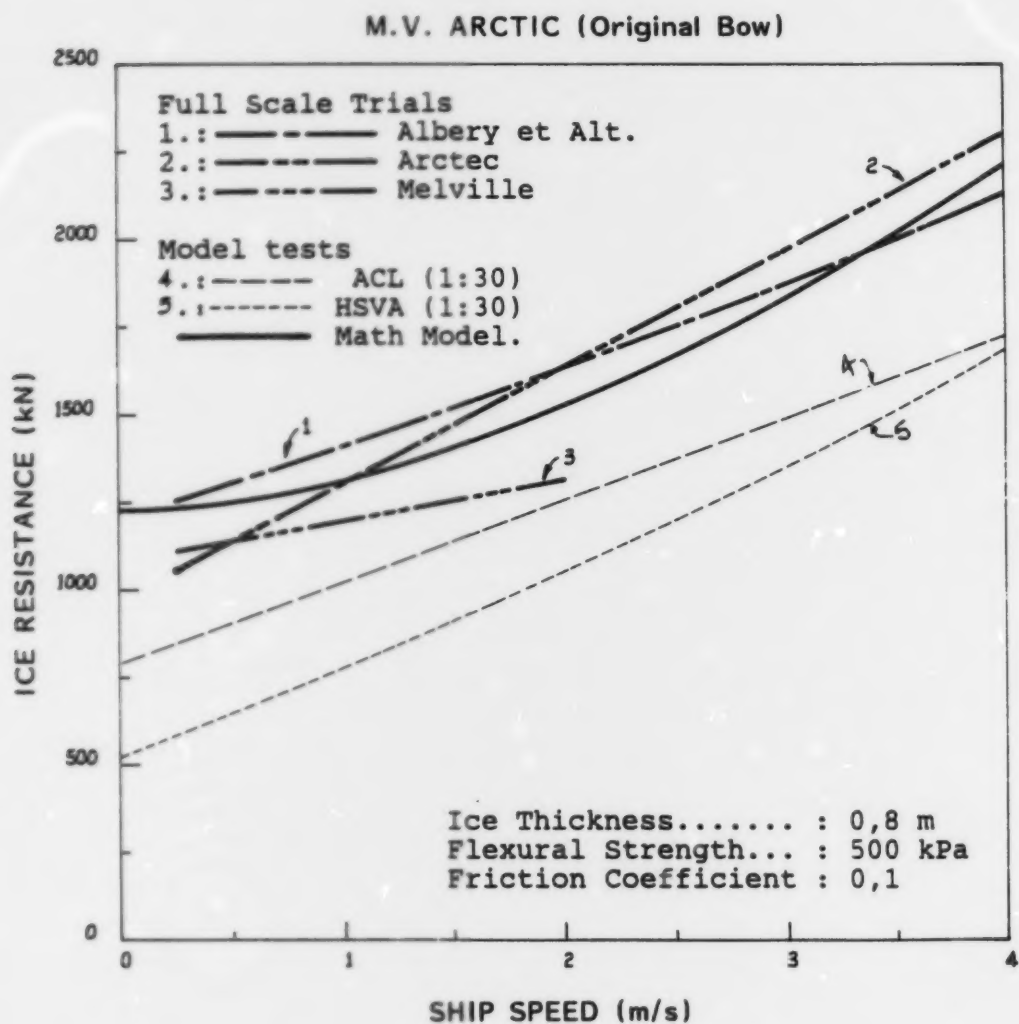
The icebreaking cargo vessel M.V. Arctic with its original bow has been model tested in 3 ice tank facilities, ACL, HSVA, and WARC. Tests were conducted in two full scale thicknesses: 0,8 m and 1,2 m. Since full scale measurements in 1,2 m are not available for comparison, we will consider only the model test results in 0,8 m ice thickness, which were run in ACL, and HSVA tanks.

The full scale ice resistance predictions based on the model tests are for $h=0,8$ m and $\sigma=500$ kPa: (Baker,D. 1984)

$$R = 786 + 234 V \quad \text{ACL (1:30)}$$

$$R = 516 + 258 V + 4 V^{2,5} \quad \text{HSVA (1:30)}$$

5.: CORRELATION ANALYSIS
 5.1.: CARTER'S MODEL VERSUS MODEL TESTS
 5.1.3:M.V. ARCTIC (Original Bow) (Cont'd)



COMPARISON BETWEEN FULL SCALE REGRESSION EQUATIONS,
 MODEL TEST RESULTS AND PREDICTIONS BY MATH MODEL.

FIGURE 5.4

5.: CORRELATION ANALYSIS
5.2.: CARTER'S MODEL VERSUS OTHER PREDICTORS

In a special report for ITTC Ice Committee, dated September 1983, Dr. R.V. Milano (1983) has exercised most analytical models available from open literature on a broad spectrum of ship types and sizes. The predictors used by Milano were:

- 1.: Kashteljan et Alt. (1968)
- 2.: Lewis and Edwards (1970)
- 3.: Edwards et Alt. (1972)
- 4.: Vance G.P. (1975)
- 5.: Enkvist E. (1972)
- 6.: Milano V.R. (1973)
- 7.: Naegle J.N. (1980)
- 8.: Naegle/Arctec in Baird and Kotras (1982)
- 9.: Carter D. (1983)

These predictors and the equations proposed by:

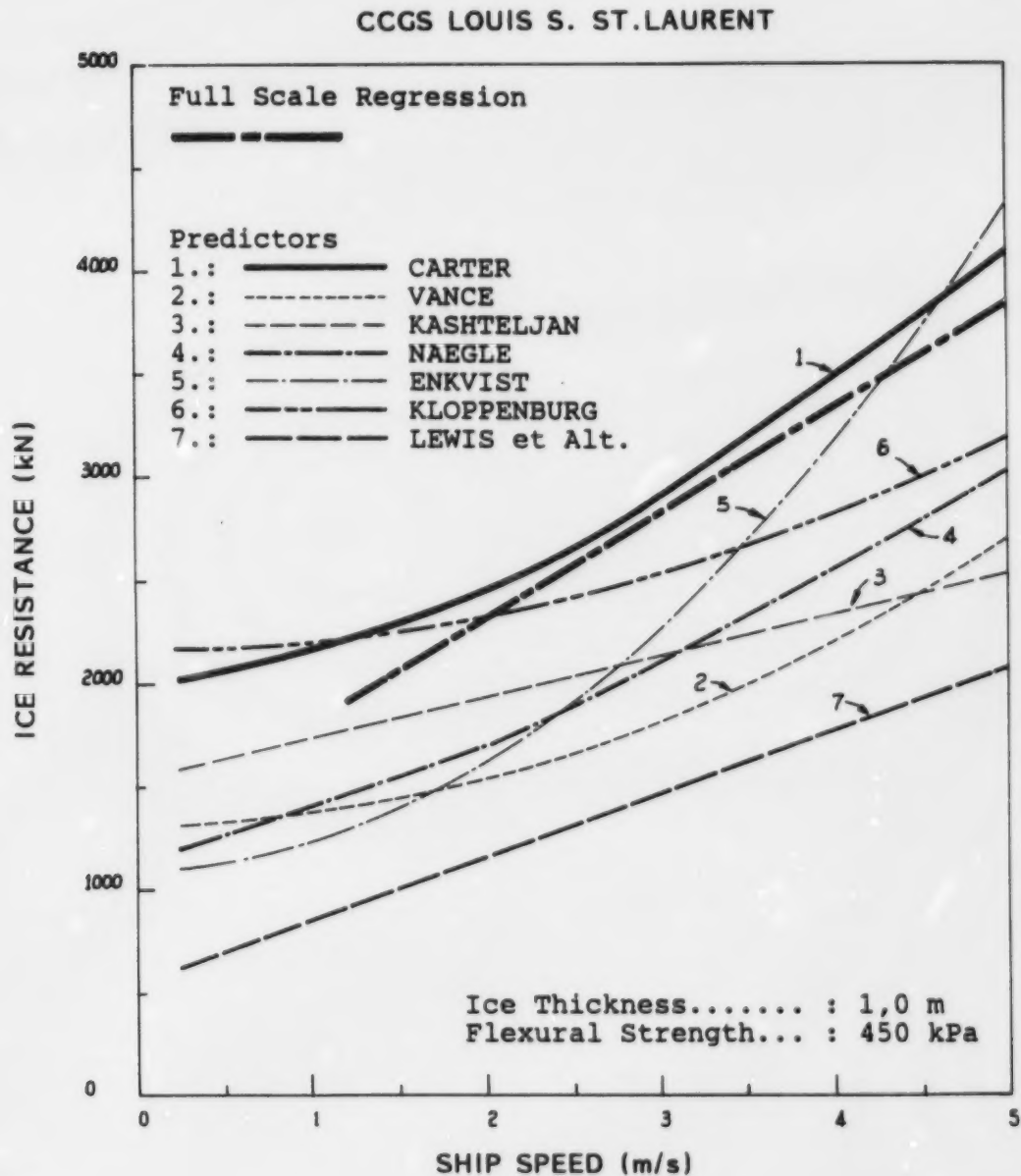
- 10.: Kloppenburg M. (1975)
- 11.: Poznyak and Ionov (1981)

will be compared with the full scale data of the three candidate ships, LOUIS S. ST. LAURENT, R-CLASS ICEBREAKER, and M.V. ARCTIC, when the predicted values are, either readily available from literature, or easily computed.

In his comparative analysis, Milano noted: (page 16)

" His (Carter's) resulting expressions for resistance are also quite simple and involve very few ship or ice parameters. Yet, as we show later, when applied to a broad spectrum of ship types, the correlation of results is quite good, and certainly better than all previous empirically derived relationships."

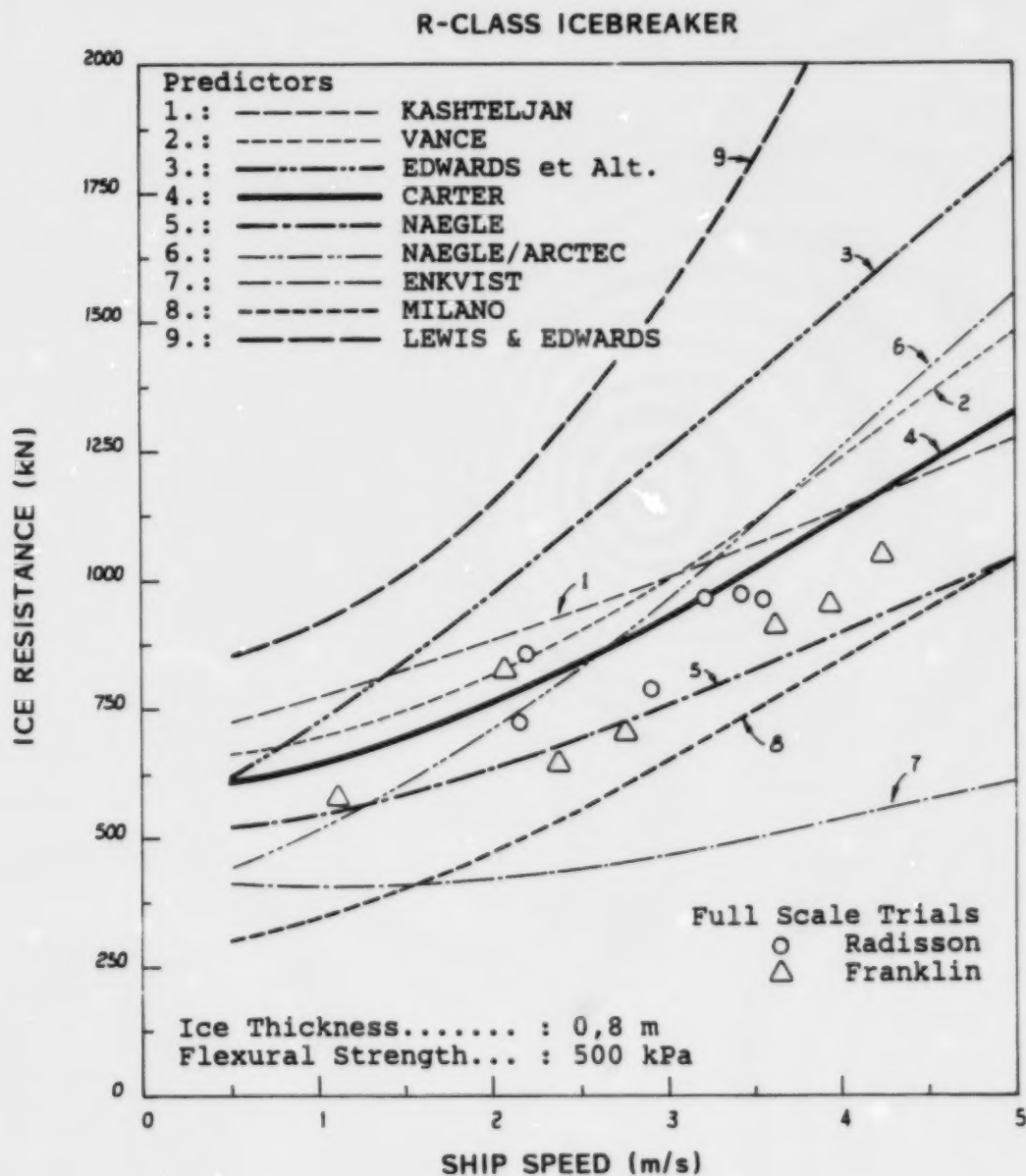
5.: CORRELATION ANALYSIS
 5.2.: CARTER'S MODEL VERSUS OTHER PREDICTORS
 5.2.1: LOUIS S. ST. LAURENT



COMPARISON BETWEEN FULL SCALE REGRESSION EQUATION,
 AND PREDICTIONS BY MATH MODEL AND OTHER PREDICTORS.

FIGURE 5.5

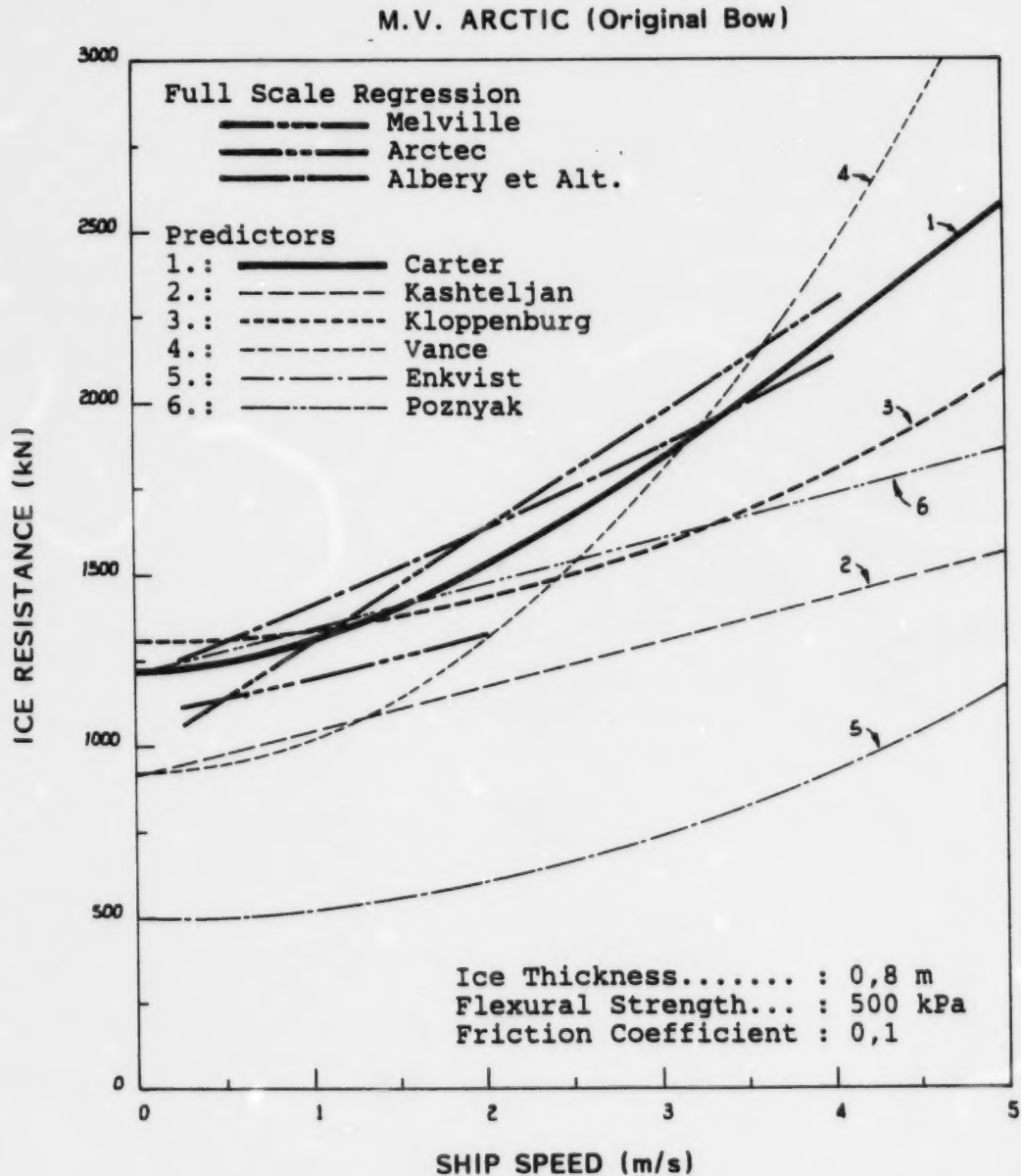
5.: CORRELATION ANALYSIS
 5.2.: CARTER'S MODEL VERSUS OTHER PREDICTORS
 5.2.2: R-CLASS ICEBREAKER



COMPARISON BETWEEN FULL SCALE REGRESSION EQUATIONS,
 AND PREDICTIONS BY MATH MODEL AND OTHER PREDICTORS.

FIGURE 5.6

5.: CORRELATION ANALYSIS
 5.2.: CARTER'S MODEL VERSUS OTHER PREDICTORS
 5.2.3:M.V. ARCTIC (Original Bow)



COMPARISON BETWEEN FULL SCALE REGRESSION EQUATIONS,
 AND PREDICTIONS BY MATH MODEL AND OTHER PREDICTORS.

FIGURE 5.7

5.: CORRELATION ANALYSIS

5.3.: CARTER'S MODEL VERSUS FULL SCALE TRIAL DATA

In this section, it is intended to demonstrate how effectively and how accurately the proposed model can predict the total resistance of various hull configurations in level ice. Towards this end, the three following ships:

- 1.: LOUIS S. ST.LAURENT (Lewis et Alt. 1982)
- 2.: VLADIVOSTOK (Moskva Type) (Enkvist 1972)
- 3.: JELPARRI (Enkvist 1972)

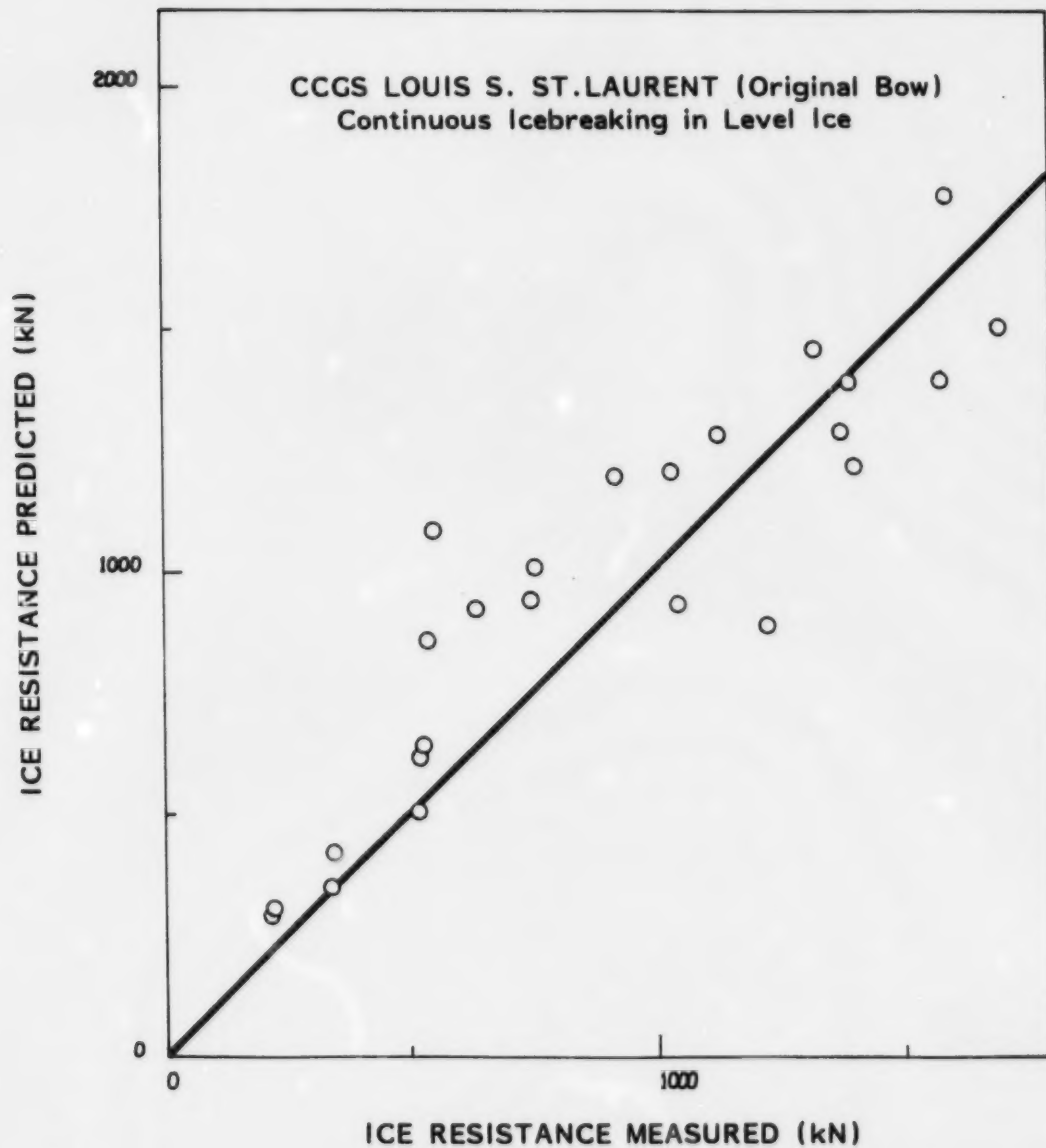
were selected for analysis on the basis of their hull configuration and the quality and quantity of available trial data.

The selected candidate ships, including the R-CLASS Icebreaker and the M.V. ARCTIC analyzed previously, cover the following range of geometrical parameters and ice properties:

Displacement	64	to	38245 tonnes
Length	15	to	197 metres
Beam	5	to	24 metres
Draft	2	to	11 metres
Stem Angle	18	to	30 degrees
Flare Angle	0	to	19 degrees
Ice Thickness	0,2	to	1,2 metres
Ice Flexural Strength	150	to	650 kPa
Ship Speed	0,5	to	7,0 m/s

Such extremes of hull configurations and ice properties should adequately confirm the flexibility, adaptability and predictive accuracy of the proposed analytical model.

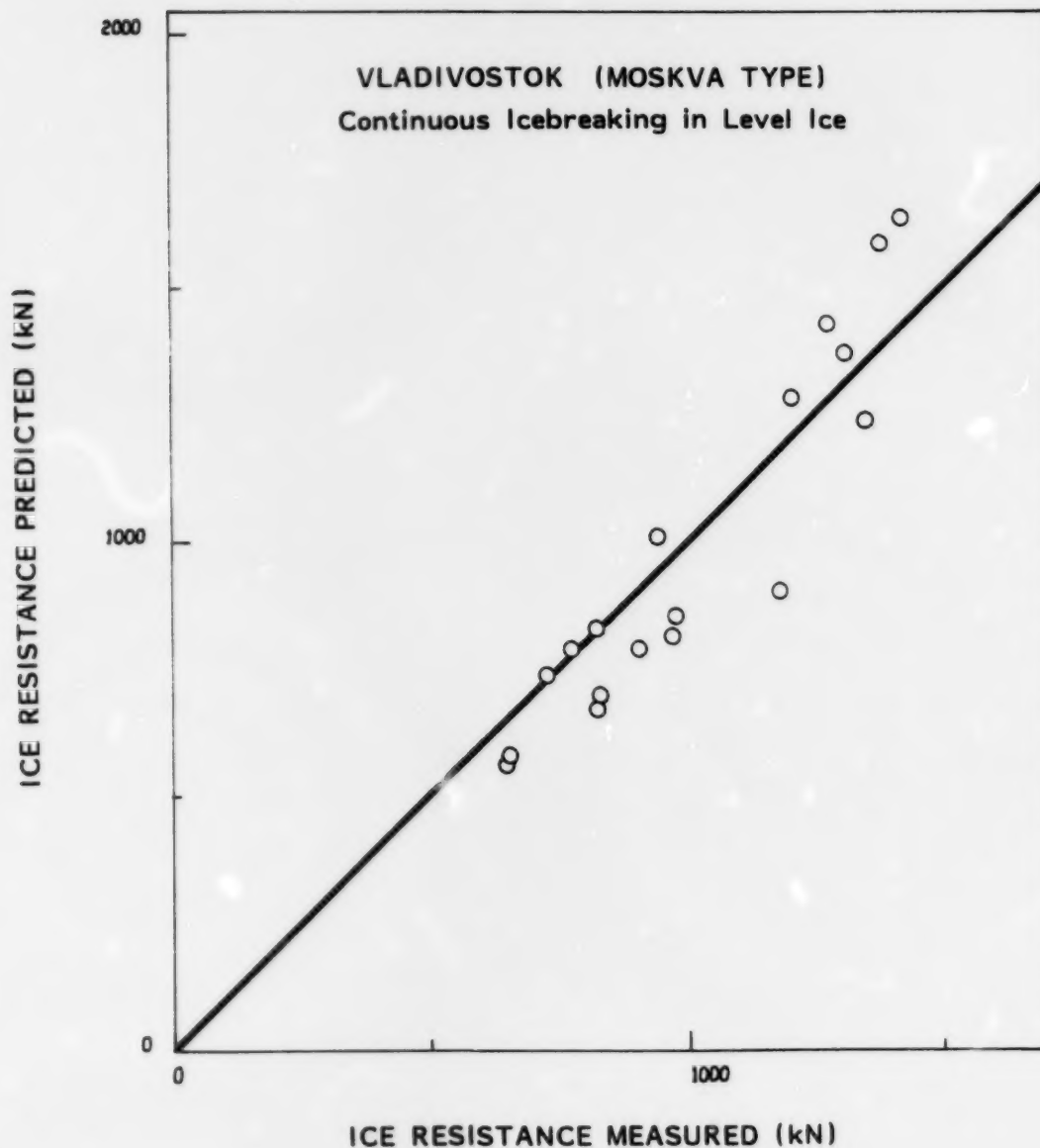
5.: CORRELATION ANALYSIS
5.3.: CARTER'S MODEL VERSUS FULL SCALE TRIAL DATA
5.3.1: LOUIS S. ST. LAURENT



COMPARISON BETWEEN ICE RESISTANCE MEASUREMENTS,
AND PREDICTIONS BY PROPOSED MATH MODEL.

FIGURE 5.8

5.: CORRELATION ANALYSIS
5.3.: CARTER'S MODEL VERSUS FULL SCALE TRIAL DATA
5.3.2: VLADIVOSTOK (MOSKVA TYPE)



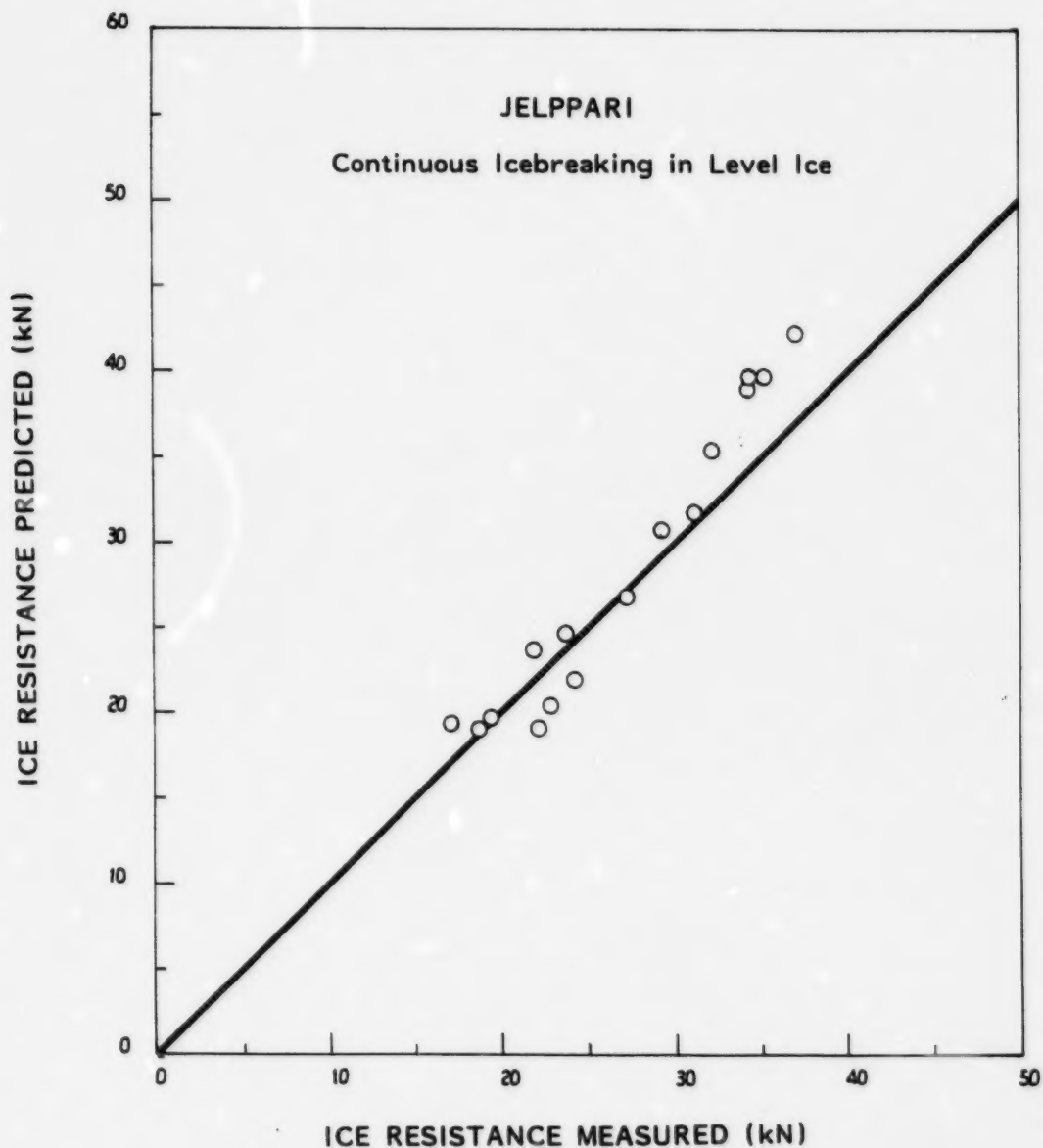
COMPARISON BETWEEN ICE RESISTANCE MEASUREMENTS,
AND PREDICTIONS BY PROPOSED MATH MODEL.

FIGURE 5.9

5.: CORRELATION ANALYSIS

5.3.: CARTER'S MODEL VERSUS FULL SCALE TRIAL DATA

5.3.3: JELPPARI



COMPARISON BETWEEN ICE RESISTANCE MEASUREMENTS,
AND PREDICTIONS BY PROPOSED MATH MODEL.

FIGURE 5.10

5.: CORRELATION ANALYSIS
5.4.: COMMENTS FROM USERS

1.: MILANO V.R.(1983) (Center for Naval Analyses)

"....., when applied to a broad spectrum of ship types, the correlation of results (obtained by Carter's model) is quite good and certainly better than all previous empirically derived relationships."

2.: TATINCLAUX J.C.(1984) (US Army Corps of Engineers)

"....., there was remarkable agreement between predictions by Carter's equation and measurements."

3.: ALBERY et Alt. (1984)

"Carter's report is particularly interesting because it offers a new analytical approach to the assessment of the resistance of sheet ice to the motion of a ship instead of one based on the theories of Kashtelyan."

4.: KENDRICK et Alt. (1988) (German and Milne)

"....., the mathematical model developed by Carter, which G & M believes to be the best overall model developed to date,....."

5.: GLEN et Alt. (1989) (Fleet Technology Ltd)

"The principle finding is that Carter's model and the segmented model's relative force distribution matched quite well in all segments. the Carter's model ... agrees quite well with all available full-scale R-Class data."

6.: INFLUENCE OF SHIP AND ICE PARAMETERS

To be useful as a predictive design tool, the math model has to be sensitive to variations in those ice and ship parameters which affect ship resistance through ice.

The present section will present the results of a systematic variation of major ship and ice parameters. Trend results will be presented in a graphical form so as to aid the reader appreciate their significance and influence on the total ship resistance in ice.

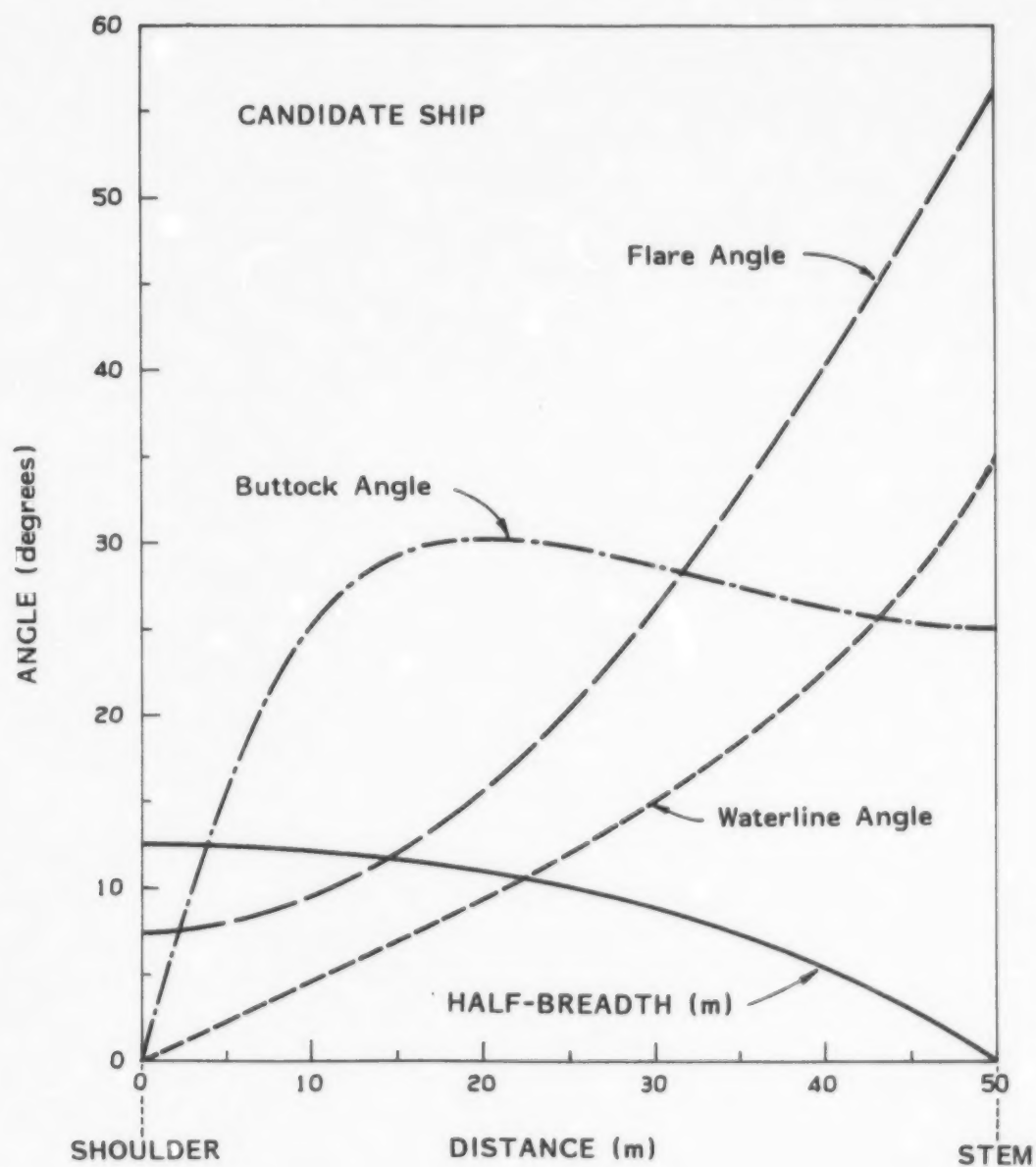
The baseline conditions around which the ice and ship parameters will be varied are as follows:

B	: Maximum Beam.....	25 m
L'	: Forebody Length.....	$2 \times B$ (50 m)
α	: Half Entrance Angle...(35°)..	$\tan^{-1} 1,4B/L'$
β	: Mid-body Flare Angle.....	7,5°
γ	: Stem Angle with Horizontal...	25°
σ	: Ice Flexural Strength.....	500 kPa
h	: Ice Thickness.....	1,0 m
f	: Friction Coefficient.....	0,1

The geometrical parameters along the bow section, determined by the use of the elliptical function presented previously, and the impact of variations in ice and hull parameters are shown graphically in the following figures.

Although the reported trend results are, strictly speaking, applicable only to the candidate ship, they are thought to be in a qualitative sense typical of all icebreakers with a so-called conventional icebreaker hull form.

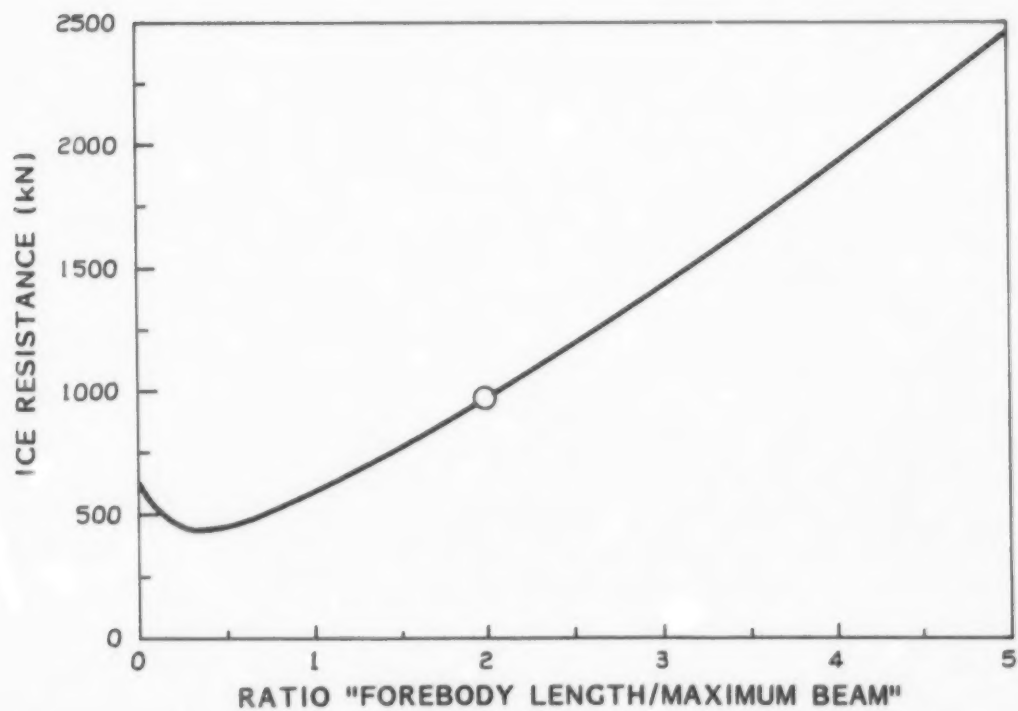
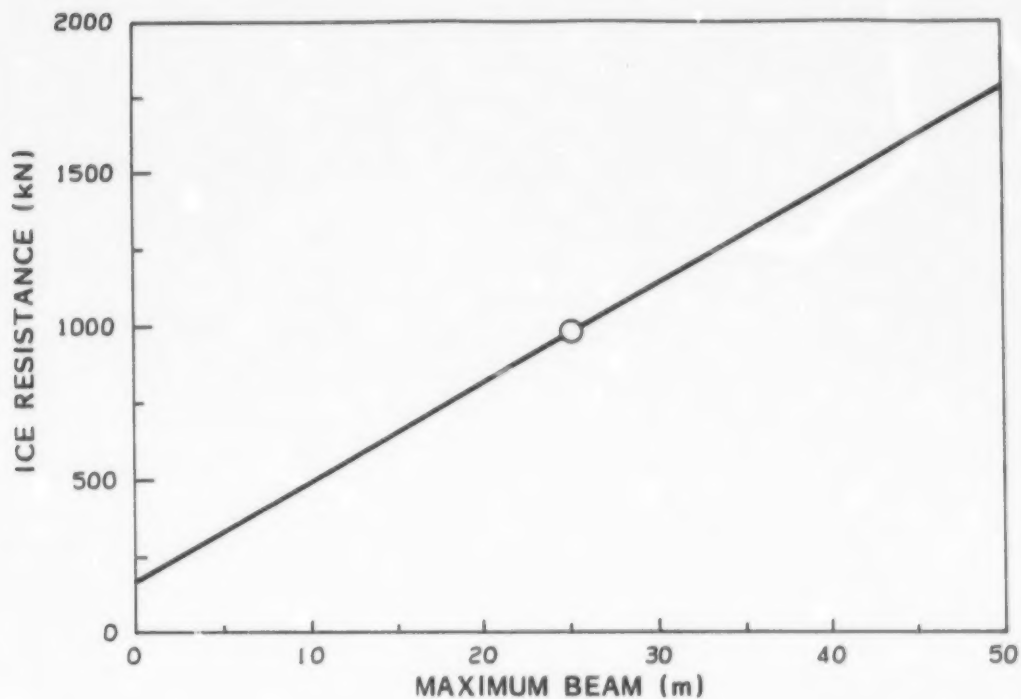
6.: INFLUENCE OF SHIP AND ICE PARAMETERS (Cont'd).



GEOMETRICAL PARAMETERS OF THE CANDIDATE SHIP
AS COMPUTED BY THE ELLIPTICAL FUNCTION.

FIGURE 6.1

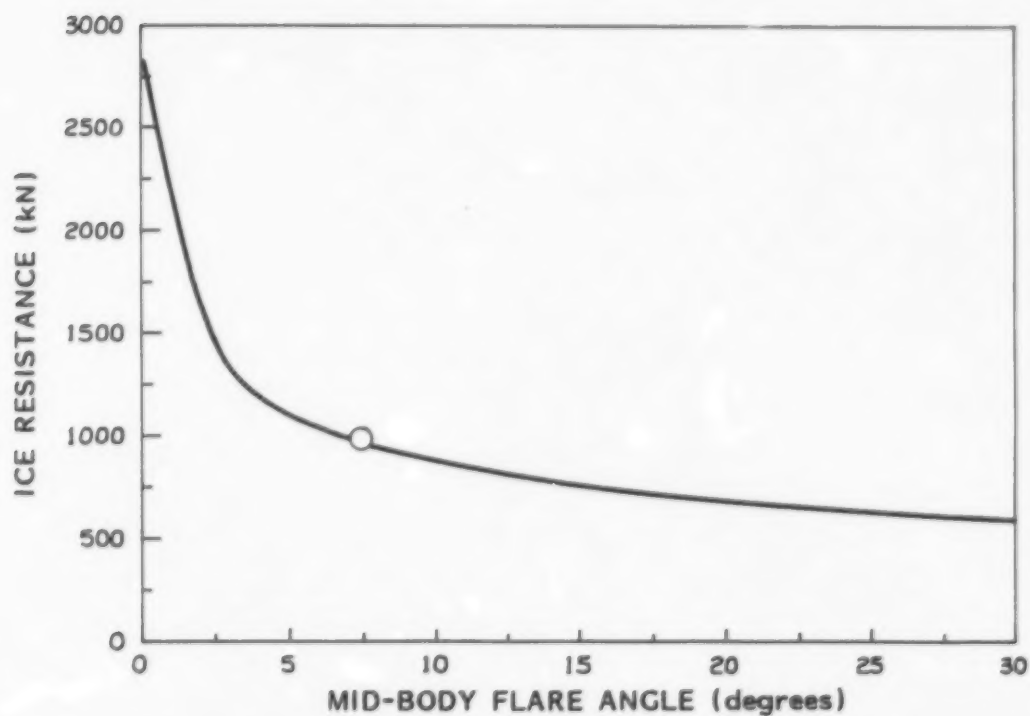
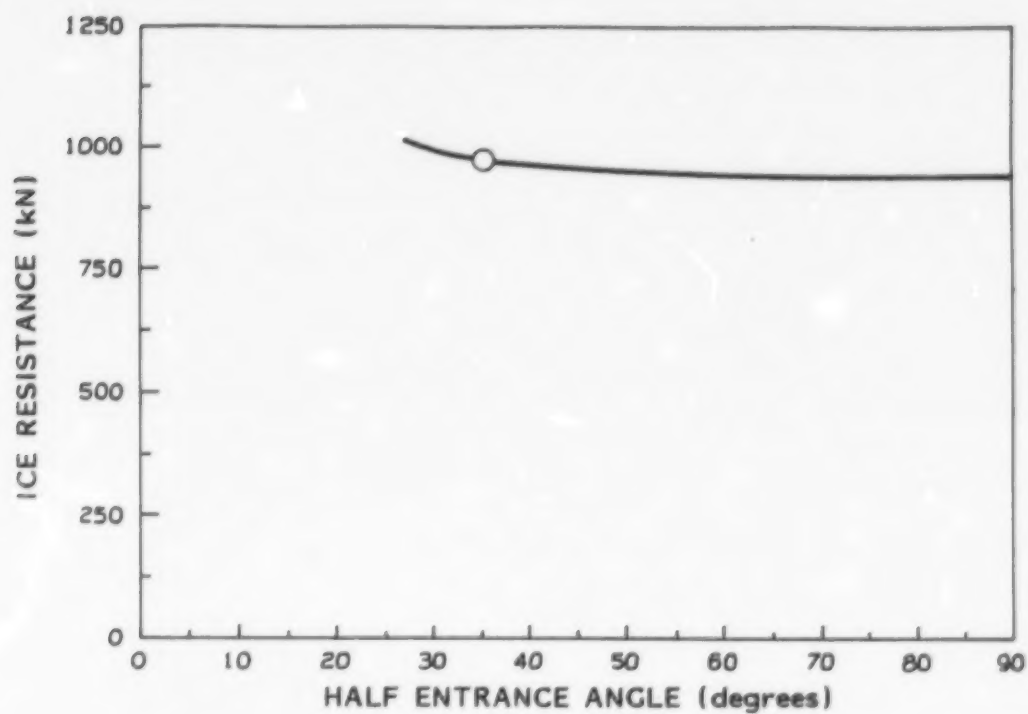
6.: INFLUENCE OF SHIP AND ICE PARAMETERS (Cont'd)



Influence of a) Maximum Beam and b) ratio "Forebody Length/Maximum Beam" on Ice Resistance.

FIGURE 6.2

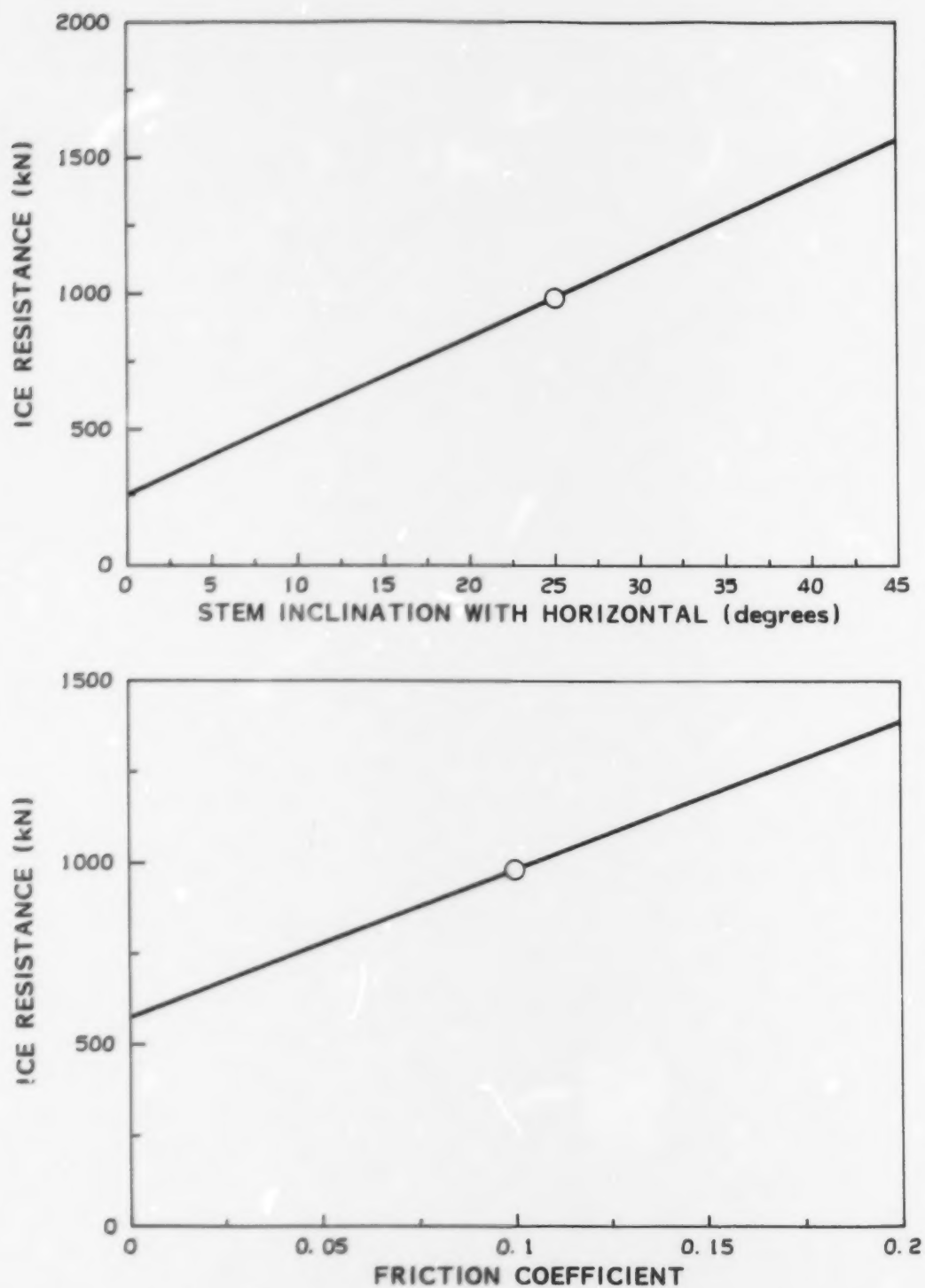
6.: INFLUENCE OF SHIP AND ICE PARAMETERS (Cont'd)



Influence of a) Half-Entrance Angle and b) Mid-Body Flare Angle on Ice Resistance.

FIGURE 6.3

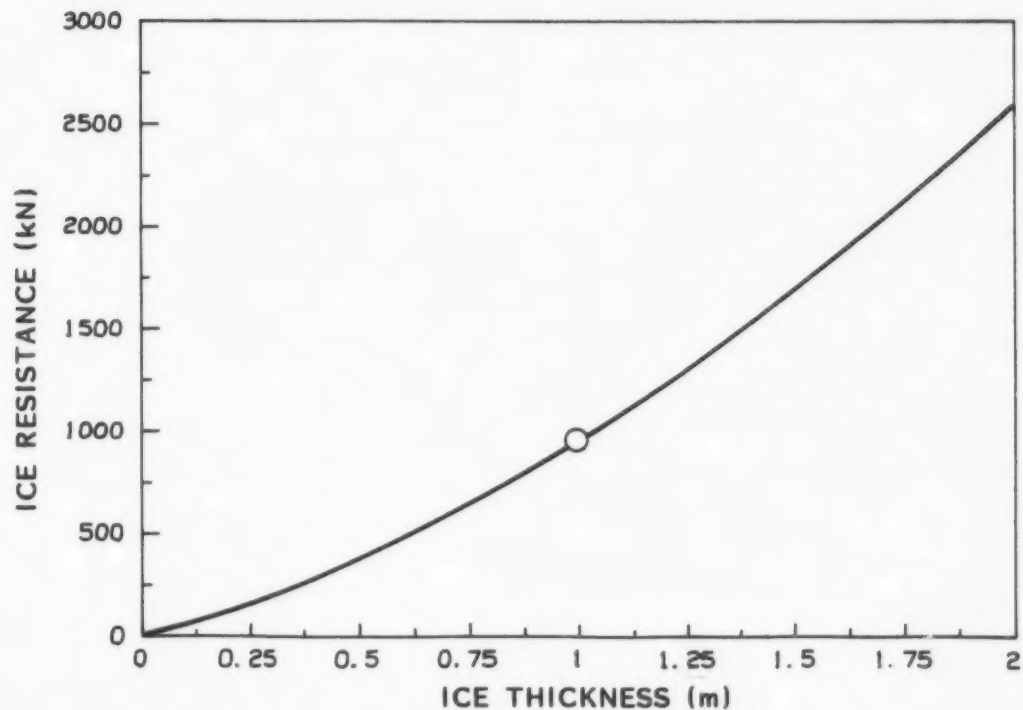
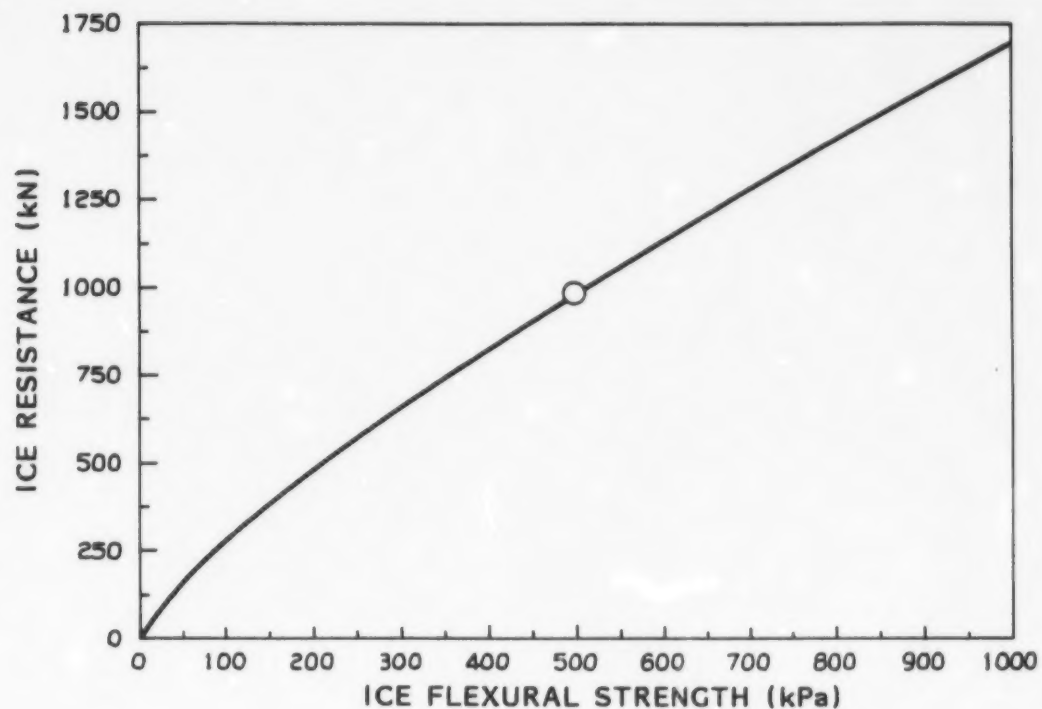
6.: INFLUENCE OF SHIP AND ICE PARAMETERS (Cont'd)



Influence of a) Stem Inclination with Horizontal and
b) Friction Coefficient on Ice Resistance.

FIGURE 6.4

6.: INFLUENCE OF SHIP AND ICE PARAMETERS (Cont'd)



Influence of a) Ice Flexural Strength and b) Ice Thickness on Ice Resistance.

FIGURE 6.5

6.: INFLUENCE OF SHIP AND ICE PARAMETERS (Cont'd)

From an analysis of the diagrams, it can be seen that mid-body flare angle and maximum beam are the two dominant parameters on total resistance, with forebody length and stem angle as the next most significant parameters followed by half entrance angle.

It is clear that most conventional bows break ice quite effectively with the forward part of the bow where waterline and flare angles are sufficiently high to develop a downward component capable of ensuring ice failure in bending.

However, further aft, when the waterline angle reduces to zero as it approaches parallel mid-body, the ice resistance distribution becomes very sensitive to the flare angle. A parallel mid-body flare angle of 0° results in ice crushing at the shoulder rather than icebreaking.

Recent bow form optimization on the basis of lower stem angle, shorter forebody length, or higher flare angle has resulted in the development of improved level icebreaking bows, such as rounded or square bow forms. It is however self-evident that these extreme shape bow forms are not optimized for open water conditions. Both the open water resistance and the seakeeping performance, especially slamming, are much poorer than for conventional icebreaker bow forms.

Following extraordinarily elaborate full-scale tests, Enkvist and Mustamaki [1986] concluded that such non-ship-shaped designs were not suitable for universal use on icebreaking ships and might be considered only for breaking thick ice on sheltered areas where rough open-water crossings were scarce.

Considering the usual mission profile of icebreakers, it is well realized that the "optimum" icebreaking bow should be the best compromise between:

- a.: Level icebreaking capability;
- b.: Performance in other ice conditions;
- c.: Hydrodynamic behavior.

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE

The ultimate aim of the study is to develop an ideal hull-ice interface which would minimize the ice resistance without unduly affecting the ship's open water performance.

To allow a systematic investigation of the effects of ship shape and size on the various mechanisms involved in breaking and moving through ice, it is very convenient to represent analytically the hull geometrical parameters. By the use of the math model, results of variations of parameters can then be viewed instantly.

The "ice belt" geometrical parameters are completely defined by:

- 1.: the design waterline;
- 2.: the flare angle distribution.

The sets of flare and waterline angles are sufficient to define the plane tangential to the bow at any discrete point along the bow branch, since they are interrelated by:

$$\tan \gamma = \frac{\tan \alpha}{\tan \beta}$$

where γ , β , α are respectively the buttock, flare and waterline angles.

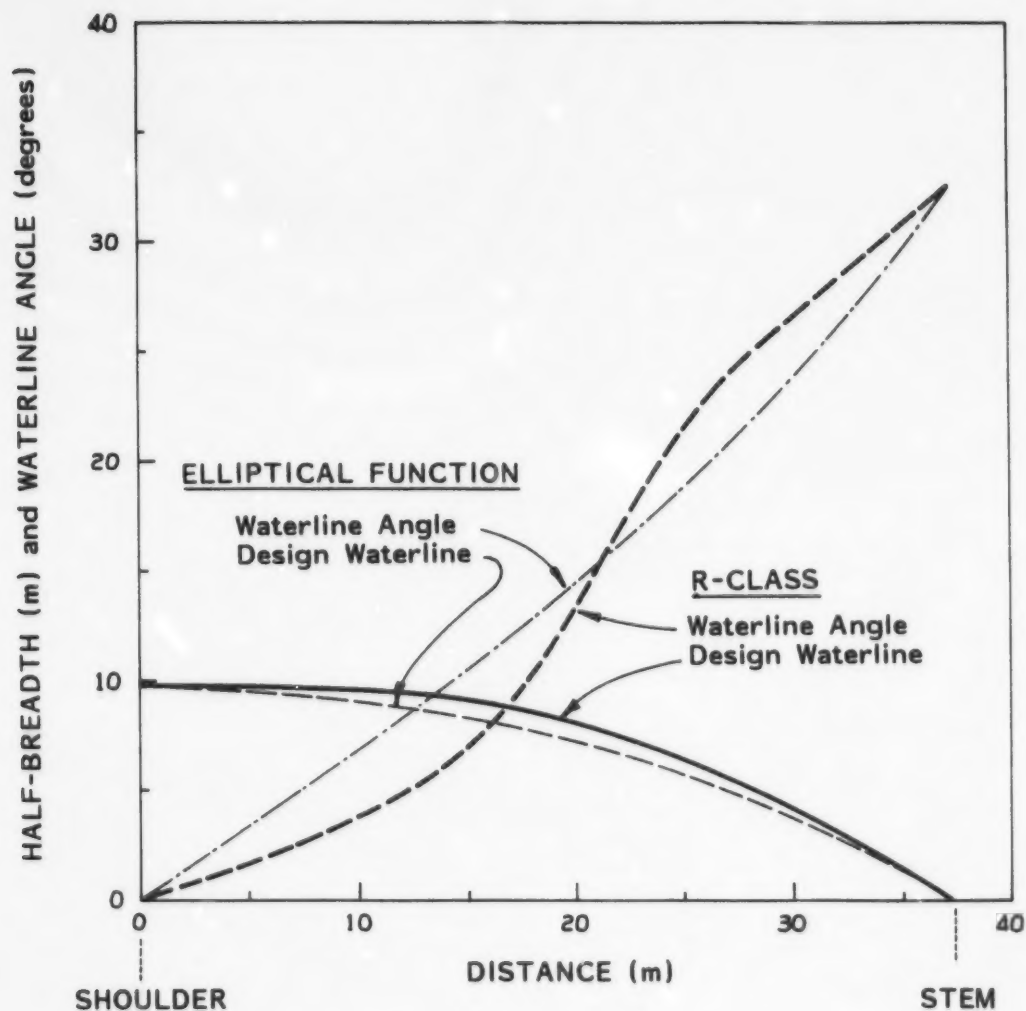
From the above equation, it can be seen that large flare angles will result in low buttock angles thereby increasing the downward force developed on the ice and reducing the likelihood of crushing.

7.1: DESIGN WATERLINE AND WATERLINE ANGLES

In the literature, besides the elliptical function presented previously, waterline shapes typical of current polar icebreakers have been represented by a quartic (4th degree) curve by Popov et al. (1973). Since the polynomial curve used by Popov et al. shows some limitations on the half entrance angle and the waterline angles and, on the other hand, lines expressed by elliptical functions

- a.: embrace all existing so-called conventional icebreakers;
 - b.: are smooth, with no point of inflection, and with curvature varying in a gradual way;
- they will be used throughout the study, unless otherwise stated.

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE (Cont'd)



COMPARISON OF R-CLASS DESIGN WATERLINE AND WATERLINE ANGLES WITH BOW BRANCH AND WATERLINE ANGLES DEFINED BY THE ELLIPTICAL FUNCTION.

FIGURE 7.1

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE

7.1: FLARE ANGLE DISTRIBUTION ALONG FOREBODY LENGTH

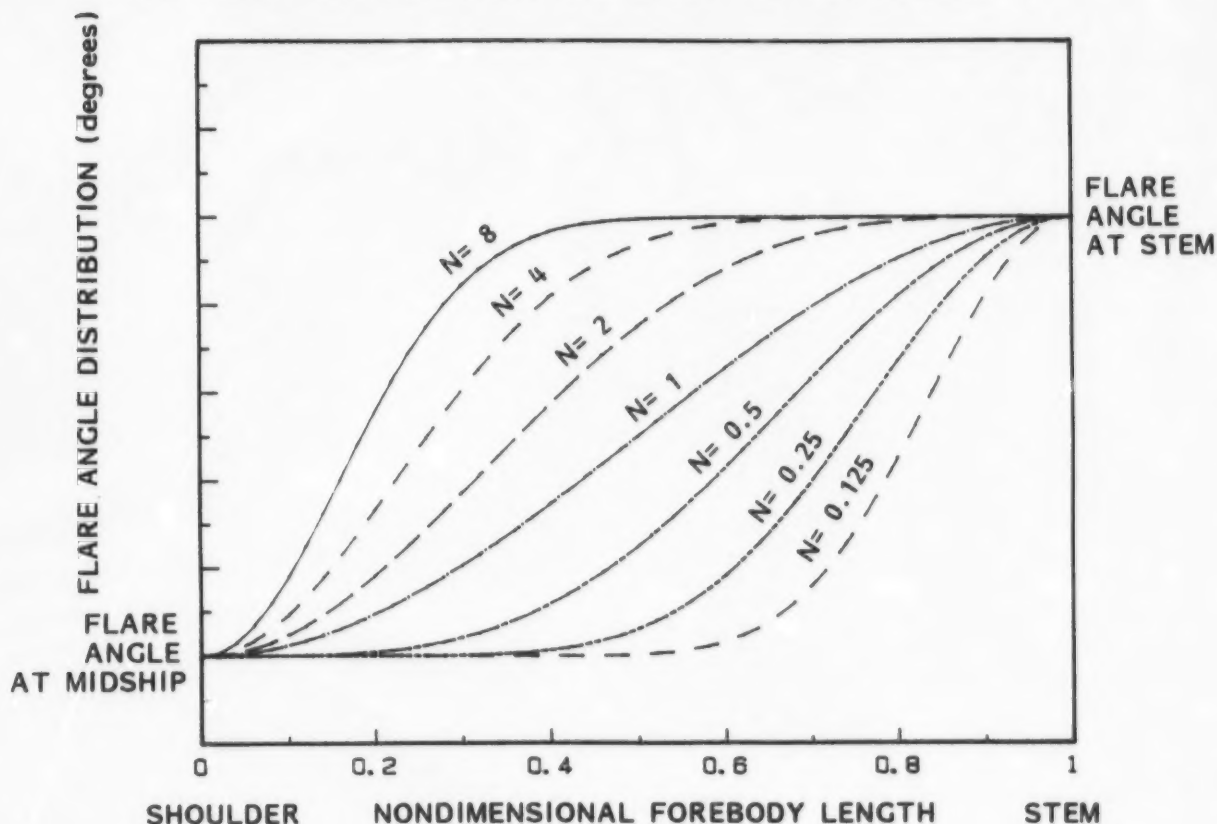
An examination of a large selection of existing and proposed icebreaker designs has indicated that the flare angle distribution along the forebody length may, in a general way, be represented by an equation of the following form:

$$\beta(x) = \beta(0) + (\beta(L') - \beta(0)) \times F_n(x, N)$$

where $F_n(x, N) = 1 - (0.5(1 - \cos \pi (1 + x/L'))^N$
for $N > 1$

and $F_n(x, N) = (0.5(1 - \cos \pi x/L'))^{\pm N}$
for $N \leq 1$

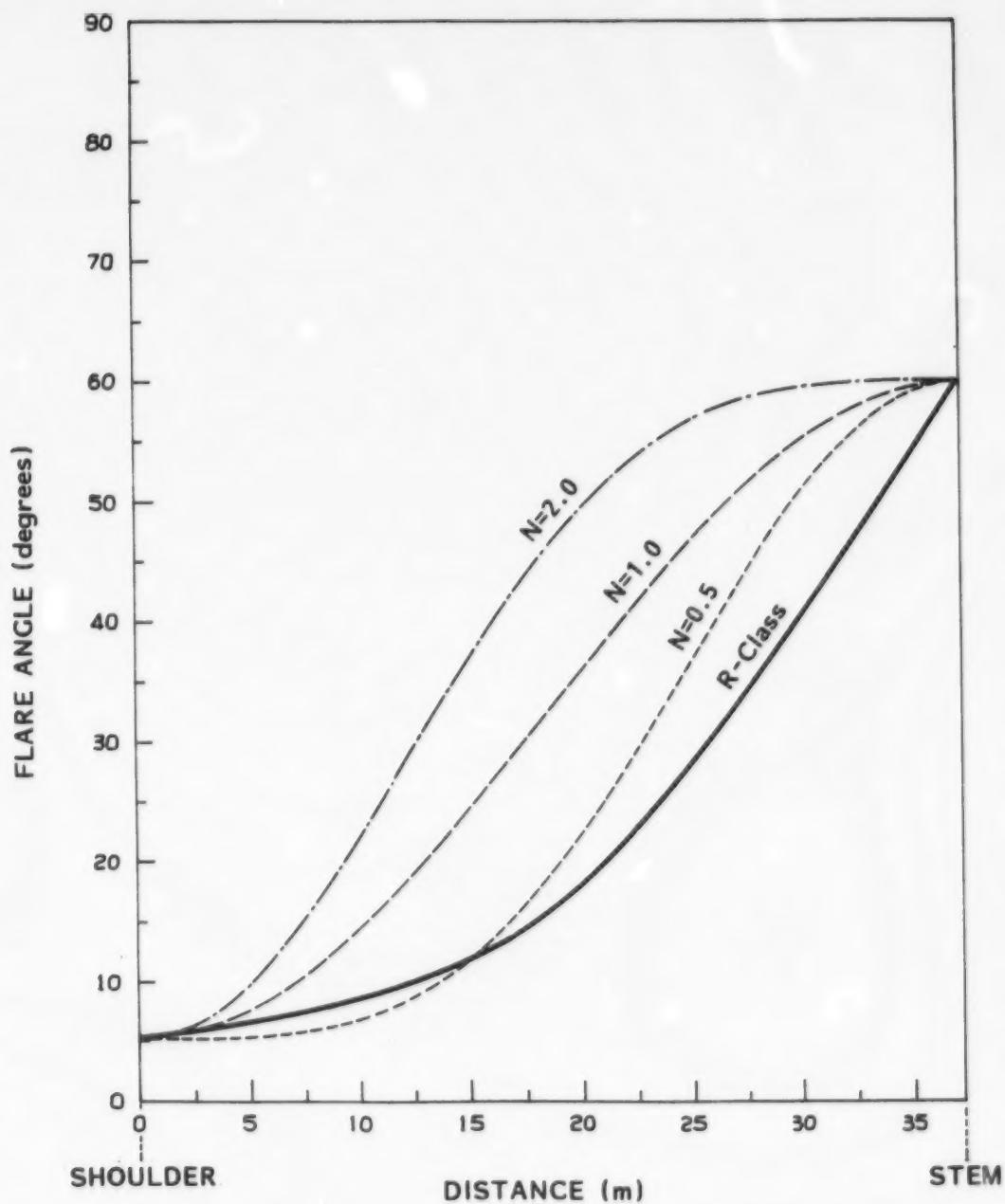
where N is an exponent in the sinusoidal function defining the flare angle distribution along the bow branch.



ANALYTICAL DISTRIBUTION OF FLARE ANGLES ALONG THE BOW SECTION AS A FUNCTION OF THE EXPONENT "N".

FIGURE 7.2

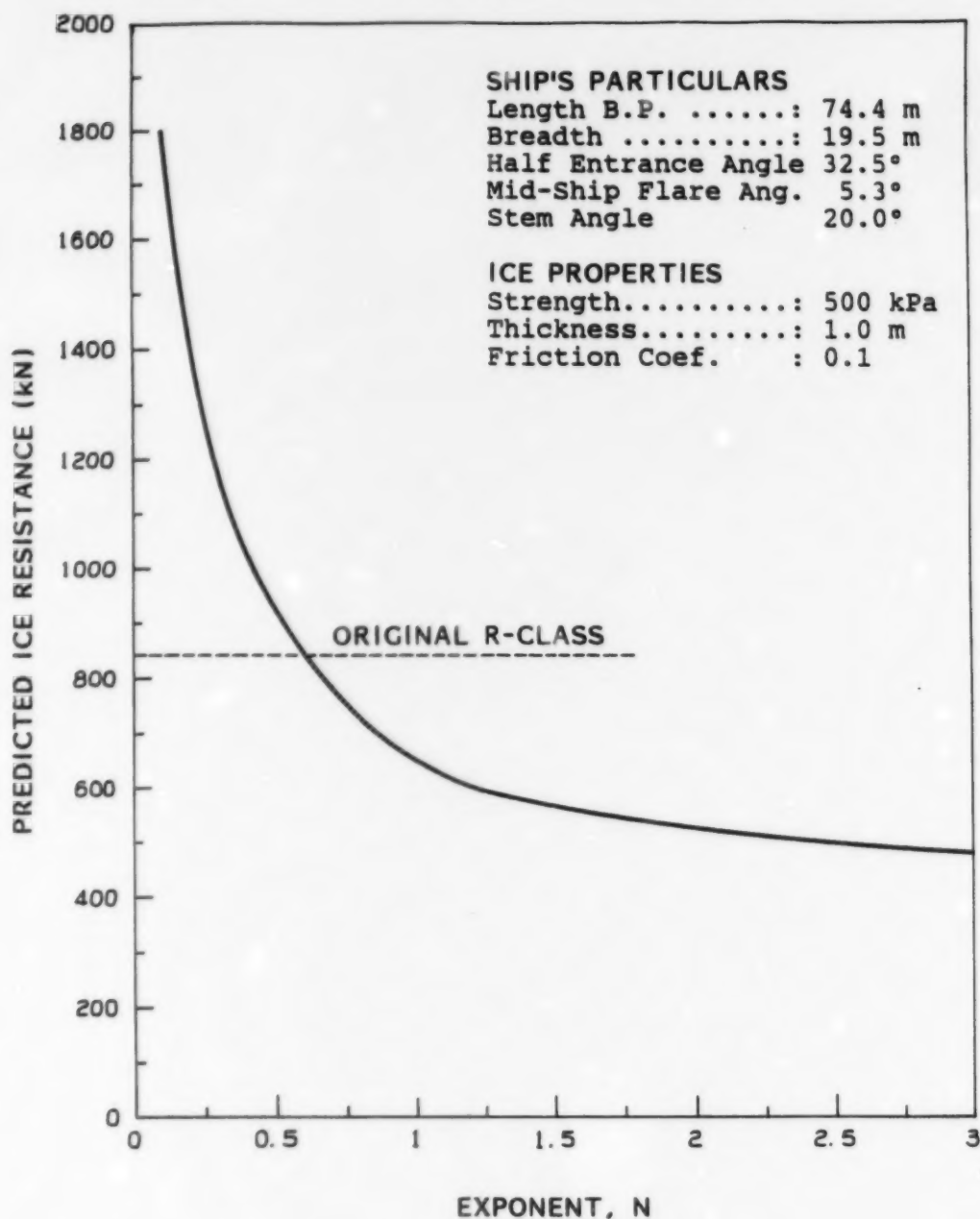
7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE
 7.2: FLARE ANGLE DISTRIBUTION ALONG FOREBODY LENGTH



COMPARISON OF ANALYTICAL DISTRIBUTIONS OF FLARE ANGLES
 ALONG FOREBODY LENGTH WITH ACTUAL R-CLASS DISTRIBUTION

FIGURE 7.3

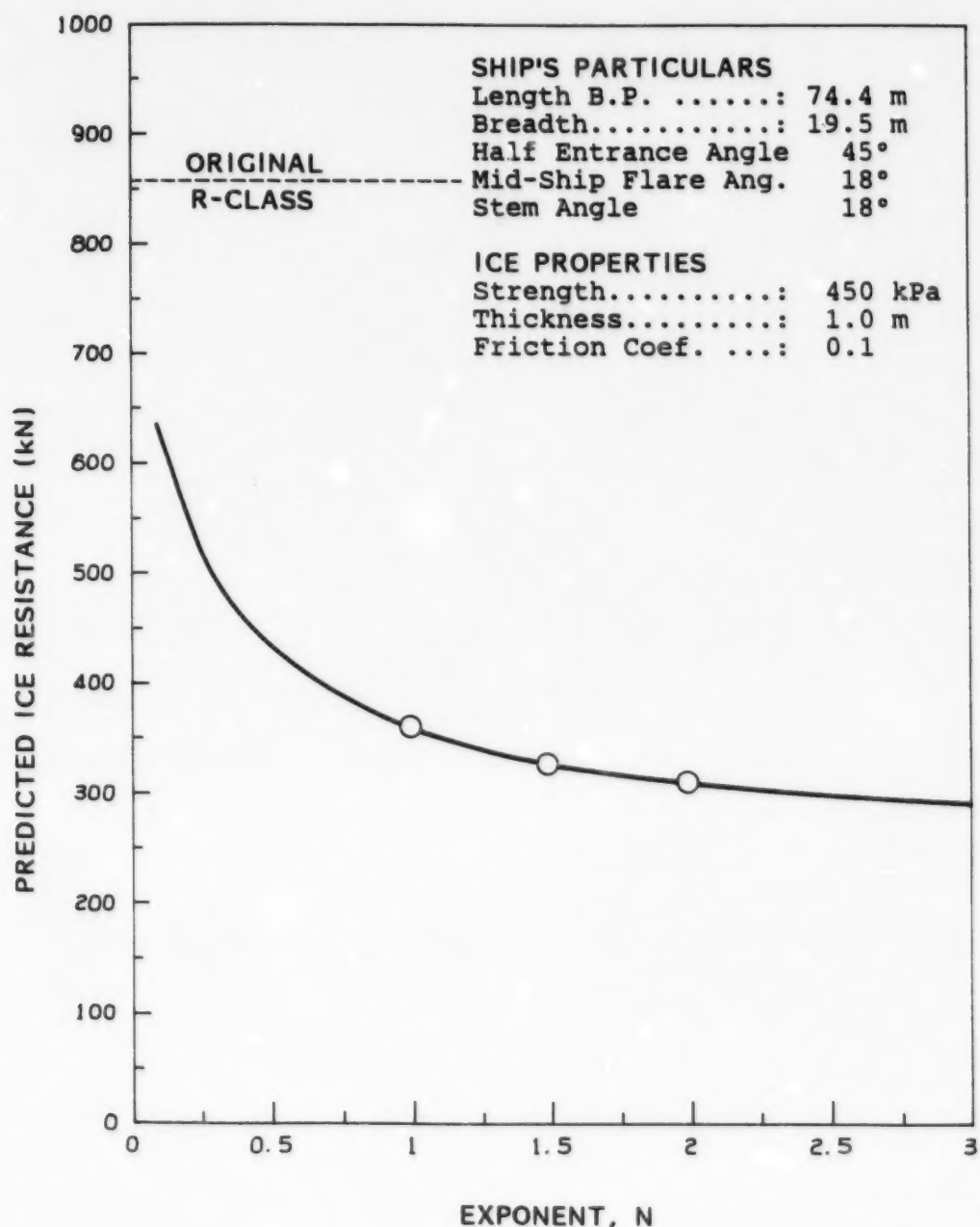
7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE
7.2: FLARE ANGLE DISTRIBUTION ALONG FOREBODY LENGTH



INFLUENCE OF THE DISTRIBUTION OF FLARE ANGLES ALONG
THE FOREBODY LENGTH ON ICE RESISTANCE.

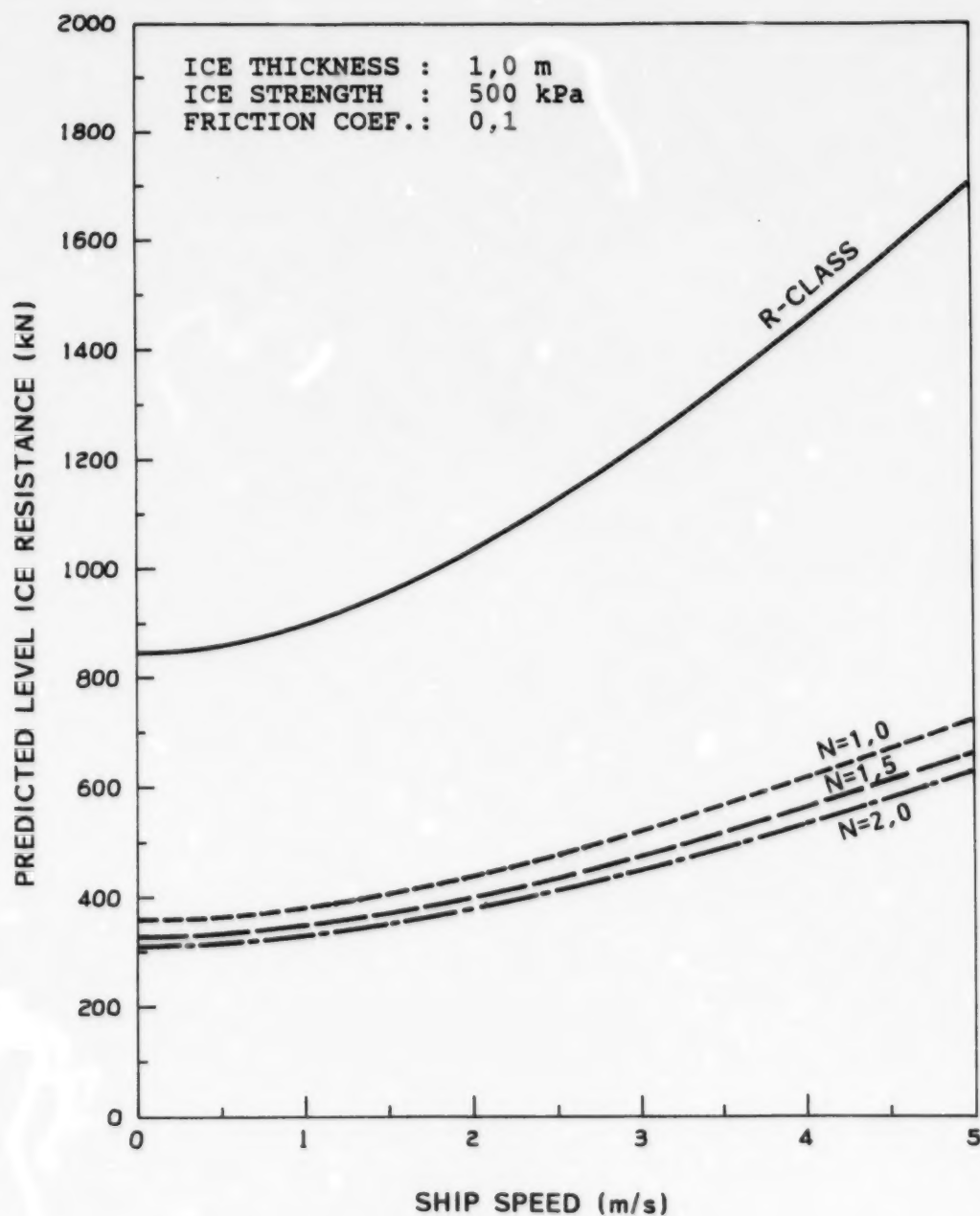
FIGURE 7.4

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE
 7.2: FLARE ANGLE DISTRIBUTION ALONG FOREBODY LENGTH



EFFECTS OF MODIFYING HALF-ENTRANCE ANGLE, MID-SHIP
 FLARE ANGLE, AND FLARE ANGLE DISTRIBUTION ALONG
 FOREBODY LENGTH.

FIGURE 7.5



PREDICTED LEVEL ICE RESISTANCE FOR THE R-CLASS
ICEBREAKER AND THE THREE PROPOSED BOW FORMS.

FIGURE 7.6

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE

7.3: CONCEPTUAL BOW FORMS

Normal icebreaking operations, as a dual process of continuous and ramming modes, require the elimination of wedging in ice or the capacity of fast and easy extraction.

Melberg et al. (1970) estimate a good multipurpose icebreaker to possess the following angles:

α :	half entrance angle.....	25 - 30°
$\beta(L')$:	flare angle at the stem.....	50 - 60°
$\beta(0)$:	flare angle at mid-ship.....	15 - 20°
γ :	bow stem angle at DWL.....	15 - 18°

A computer program was developed to generate, from principal particulars selected by the user, unfair body lines with various distributions of flare angles along the forebody length. These unfair lines can be used as input data for conventional hull definition programs.

As examples, three alternate bows will be developed from the R-Class to have the same overall size and displacement, but by modifying the distribution of waterline and flare angles along the forebody length, achieve a better icebreaking performance.

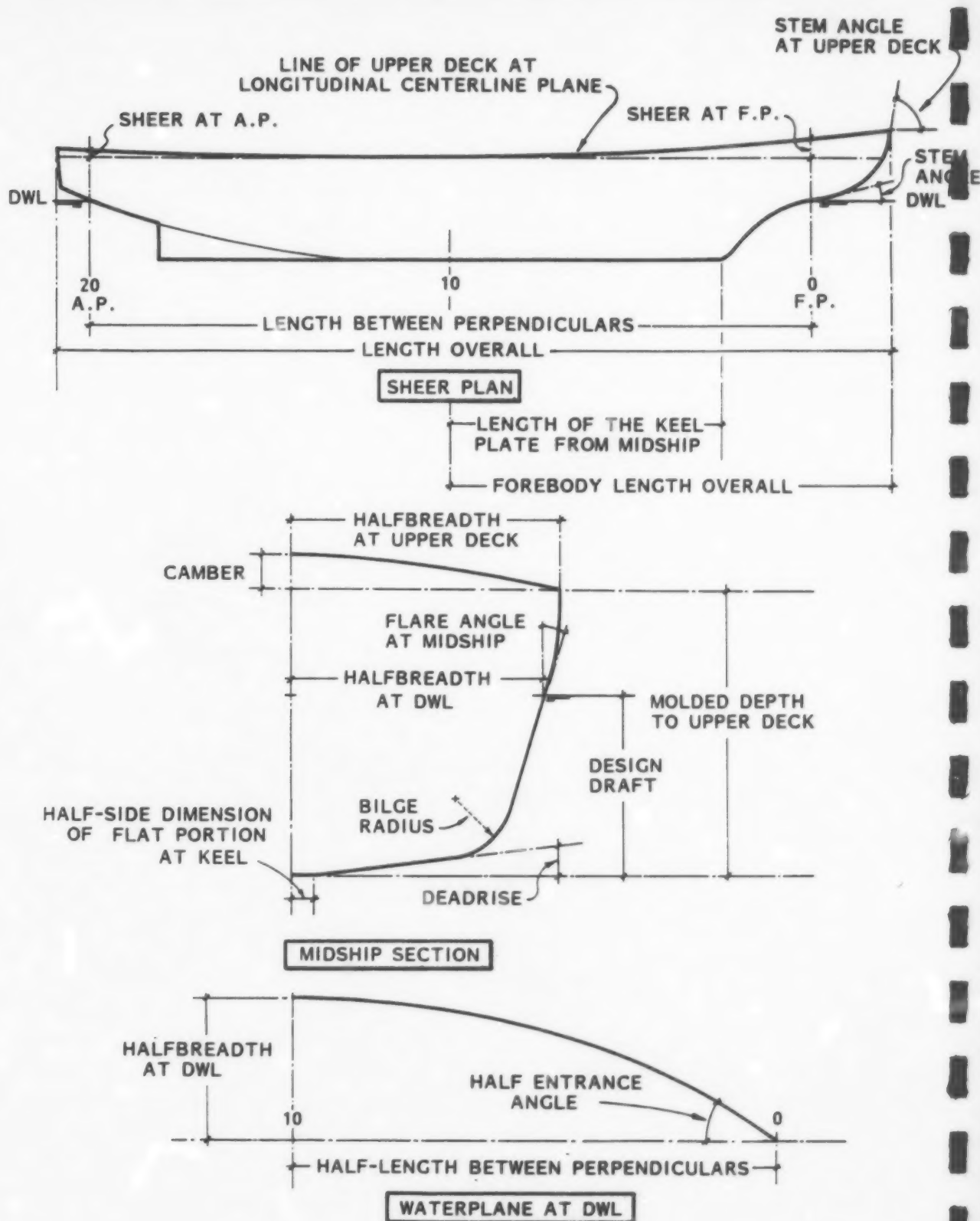
The retained principal particulars are:

LENGTH OVERALL.....	98.32 m
LENGTH B.P.	87.94 m
BREADTH AT DWL	19.35 m
DESIGN DRAFT	7.16 m
HALF ENTRANCE ANGLE	45°
MID-BODY FLARE ANGLE	18°
STEM ANGLE AT DWL	18°

and the exponent, N , in the flare angle function is successively taken as 1,0 (Bow A), 1,5 (Bow B), and 2,0 (Bow C).

The analytical assessment of the seakeeping performance was made, for the R-Class and the three alternate bow forms, using the Standard Ship Motion Program (SHIPMO).

The selected results, presented in TABLE 7.1, show no significant effect on heave acceleration and slamming pressure.



DESIGNER-CONTROLLED SHIP PARAMETERS IN THE PROGRAM "OPTIBOW"

FIGURE 7.7

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE
7.3: CONCEPTUAL BOW FORMS (Cont'd)

PRINCIPAL GEOMETRIC CHARACTERISTICS
R-Class; Hull"A"N=1,0; Hull"B"N=1,5; Hull"C"N=2,0

LENGTH OVERALL 98,32 m
LENGTH B.P. 87,94 m
BREADTH MLD (UPPER DECK) 20,12 m
BREADTH MLD (DESIGN WATERLINE) 19,35 m
DEPTH MLD (UPPER DECK) 10,83 m
DRAFT MLD (DESIGN WATERLINE) 7,16 m
CAMBER 0,30 m
SHEER FORWARD 1,98 m
SHEER AFT 0,61 m
RATIO OF LENGTH TO BREADTH 4,54
RATIO OF LENGTH TO DRAFT 12,28
RATIO OF BREADTH TO DRAFT 2,70

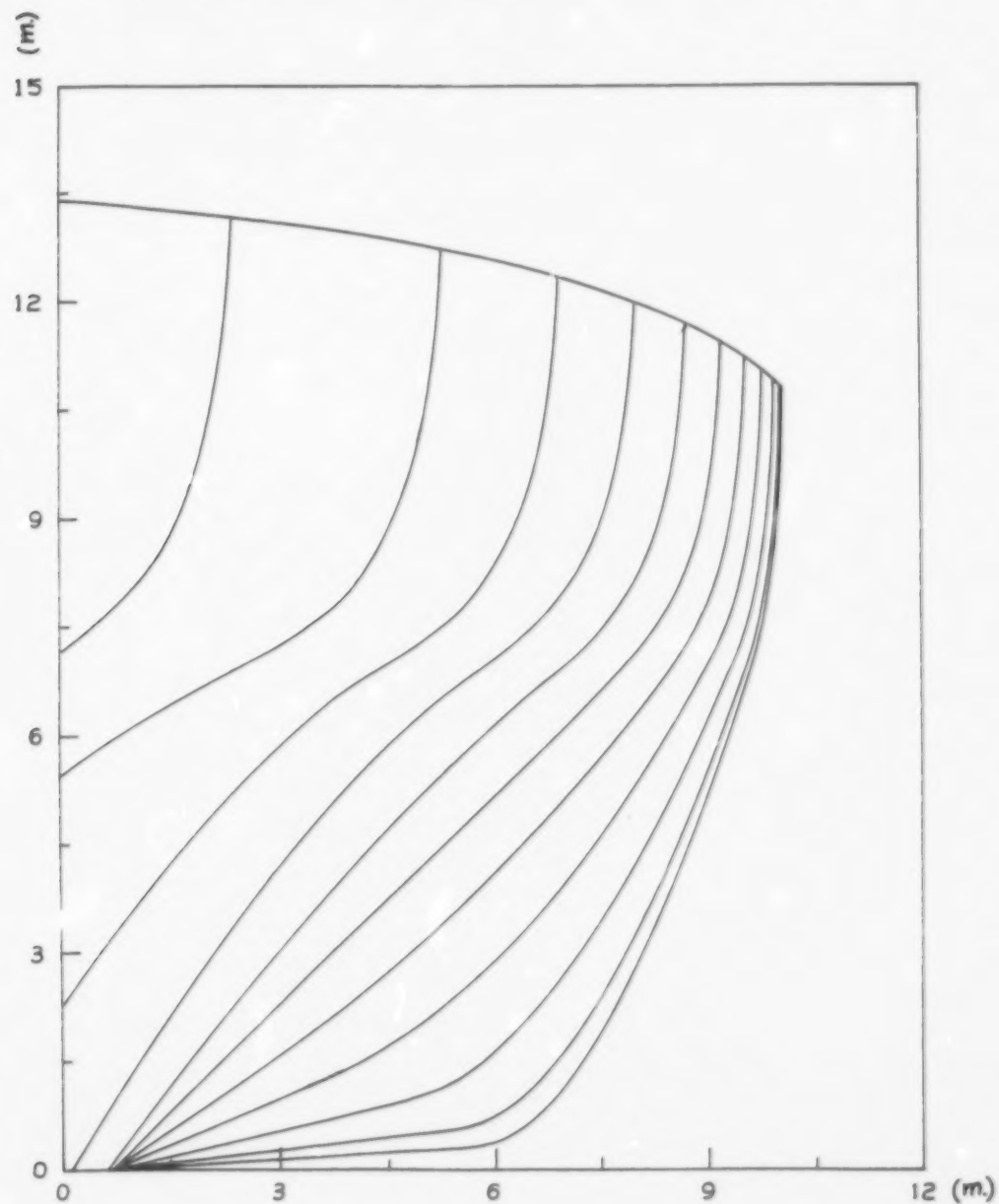
	R-Class	Hull"A"	Hull"B"	Hull"C"
BLOCK COEFFICIENT	0,625	0,520	0,520	0,514
FOREBODY BLOCK COEF.	0,564	0,480	0,480	0,465
MIDSHIP COEFFICIENT	0,911	0,840	0,840	0,840
PRISMATIC COEFFICIENT ..	0,683	0,620	0,620	0,611
WATERPLANE COEFFICIENT .:	0,791	0,800	0,800	0,800
F'BODY WATERPLANE COEF. :	0,762	0,736	0,736	0,736

FOREBODY WATERPLANE ANGLES

STATION	WATERLINE ANGLE, α°				FRAME FLARE ANGLE, β°			
	R-Class	Hull"A"	Hull"B"	Hull"C"	R-Class	Hull"A"	Hull"B"	Hull"C"
0	32,50	45,00	45,00	45,00	60,00	72,00	72,00	72,00
$\frac{1}{2}$	31,25	33,08	33,08	33,08	54,91	71,67	71,97	72,00
1	29,66	26,72	26,72	26,72	49,51	70,68	71,79	72,97
$1\frac{1}{2}$	27,97	22,50	22,50	22,50	44,51	69,06	71,31	71,84
2	26,41	19,40	19,40	19,40	39,92	66,84	70,41	71,51
3	22,79	14,92	14,92	14,92	30,78	60,87	66,95	69,71
4	17,39	11,70	11,70	11,70	22,77	53,34	61,03	65,55
5	11,30	9,13	9,13	9,13	16,00	45,00	52,91	58,50
6	7,03	6,97	6,97	6,97	11,71	36,66	43,41	48,87
7	4,43	5,05	5,05	5,05	9,32	29,13	33,80	37,97
8	2,68	3,29	3,29	3,29	7,77	23,16	25,55	27,82
9	1,26	1,62	1,62	1,62	6,48	19,32	19,97	20,61
10	0,00	0,00	0,00	0,00	5,30	18,00	18,00	18,00

Stations are numbered from the bow, with FP designated as STATION 0 and AP as STATION 20.

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE
7.3: CONCEPTUAL BOW FORMS (Cont'd)

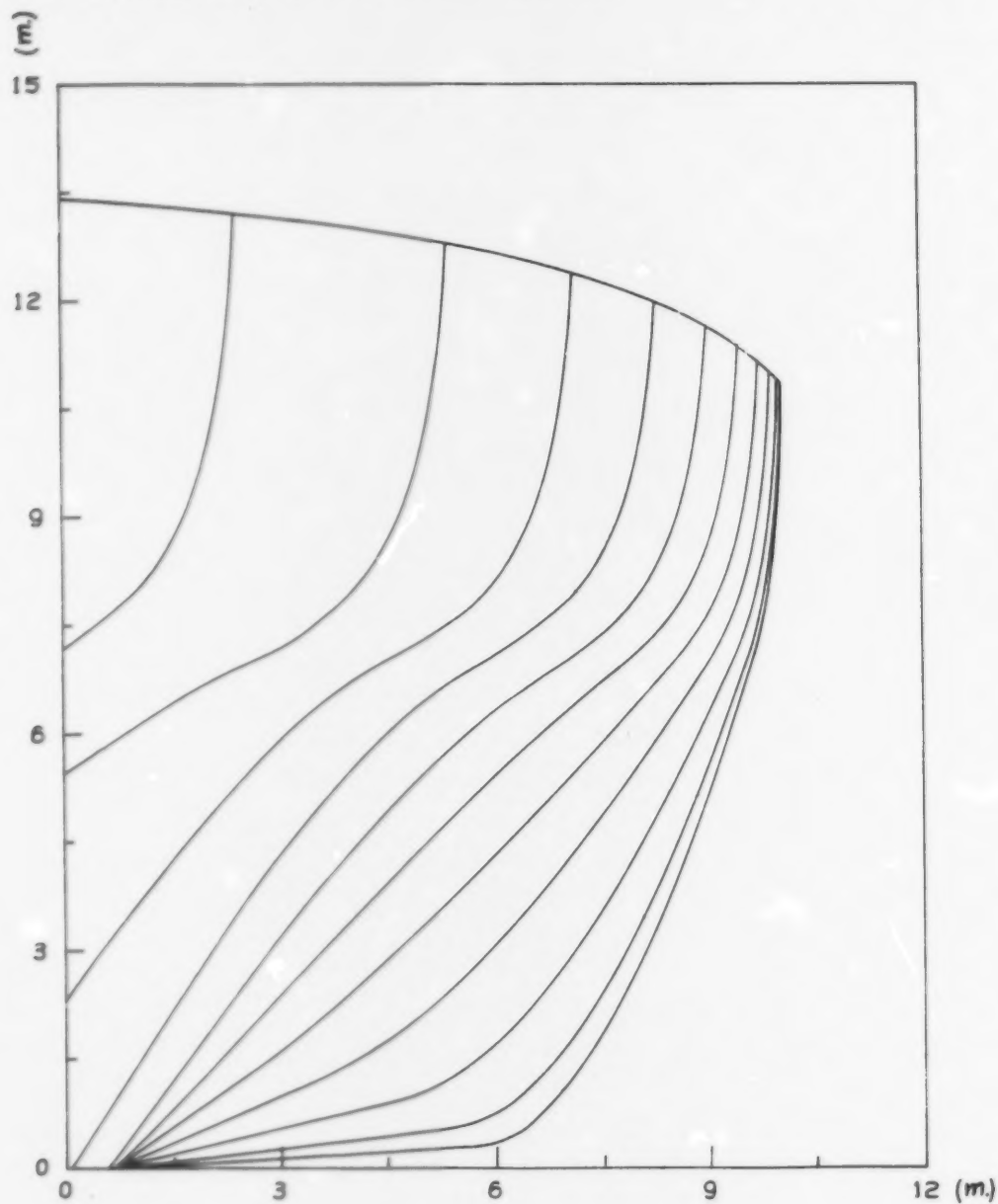


UNFAIR FOREBODY PLAN --- EXPONENT = 1.0

UNFAIR LINES OBTAINED FROM THE PROGRAM "OPTIBOW" TO BE
USED AS INPUT DATA IN STANDARD HULL DEFINITION PROGRAMS

FIGURE 7.8

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE
7.3: CONCEPTUAL BOW FORMS (Cont'd)

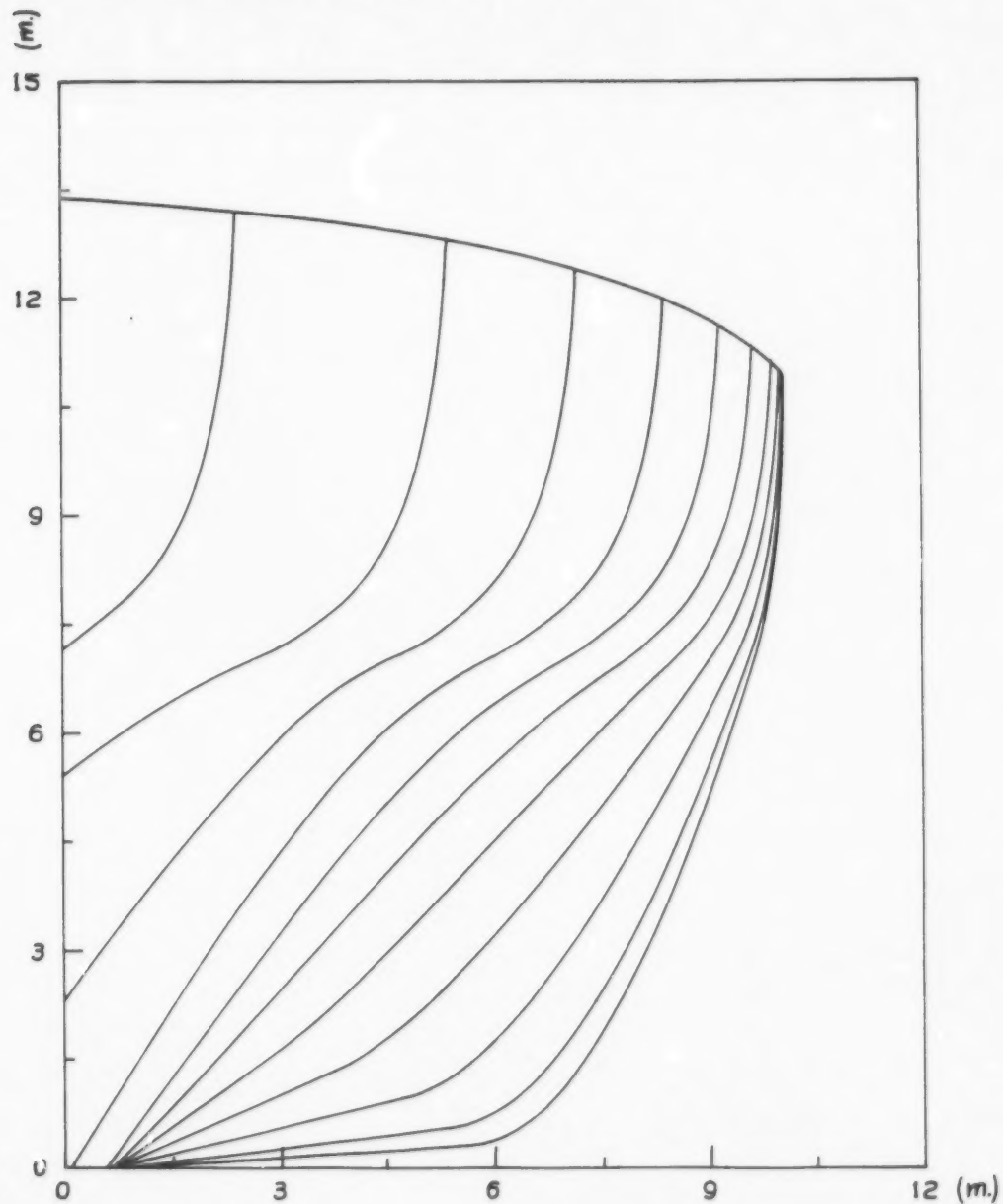


UNFAIR FOREBODY PLAN --- EXPONENT = 1.5

UNFAIR LINES OBTAINED FROM THE PROGRAM "OPTIBOW" TO BE
USED AS INPUT DATA IN STANDARD HULL DEFINITION PROGRAMS

FIGURE 7.9

7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE
 7.3: CONCEPTUAL BOW FORMS (Cont'd)



UNFAIR FOREBODY PLAN --- EXPONENT = 2.0

UNFAIR LINES OBTAINED FROM THE PROGRAM "OPTIBOW" TO BE
 USED AS INPUT DATA IN STANDARD HULL DEFINITION PROGRAMS

FIGURE 7.10

TABLE 7.1

ANALYTICAL SEAKEEPING ASSESSMENT

Significant Wave Height : 3,25 m

Modal Wave Period : 10,0 s

Heading : 180 (°)

Ship Velocity : 18,0 knots

Sea State : 5

in unidirectional seas

STATION	HEAVE ACCELERATION (in g)			
	R-Class	Bow "A"	Bow "B"	Bow "C"
2 at DWL	0,201	0,175	0,166	0,169
3 at DWL	0,184	0,159	0,151	0,153
4 at DWL	0,168	0,144	0,136	0,138
MOST PROBABLE SLAMMING PRESSURE (kPa)				
2 at DWL	33,18	29,06	24,73	25,60

in short-crested seas

STATION	HEAVE ACCELERATION (in g)			
	R-Class	Bow "A"	Bow "B"	Bow "C"
2 at DWL	0,189	0,171	0,163	0,166
3 at DWL	0,173	0,156	0,148	0,151
4 at DWL	0,158	0,141	0,134	0,136
MOST PROBABLE SLAMMING PRESSURE (kPa)				
2 at DWL	22,80	24,21	20,19	20,93



7.: BOW FORM OPTIMIZATION FOR ICE PERFORMANCE

7.3: CONCEPTUAL BOW FORMS (Cont'd)

Once defined by the program "OPTIBOW", the three preliminary sets of lines were supplied to Réjean Desgagnés, a naval architect, for final fairing.

By the use of a ship hull form generator program called MACSURF which puts the fairing capability under the control and the judgment of the operator, the hull form above and below the "ice belt" was as slightly as possible modified to:

- a.: satisfy practical ship design requirements;
- b.: achieve consistency among the various views.

The hull-ice interface at plus and minus 1 m above and below the design waterline, optimized for icebreaking performance, was kept unchanged.

In accordance with the usual practice, the various geometric parameters, section offsets, and other data required to completely delineate the three conceptual bow forms were generated and presented in the following Tables and Figures.

The three conceptual bow forms are not based on particular considerations of displacement, capacity, or propulsion to meet specific mission profiles and must be viewed only as examples to illustrate the use of the model in the process of optimizing icebreaking performance.



TABLE OF OFFSETS HULL FORM "A" (N=1.0)

WATER- LINES.	STATIONS NUMBERED FROM THE BOW (FP DESIGNATED AS STATION 0 AND AP AS STATION 20)												
	-1	-0.5	0	1	2	3	4	5	6	7	8	9	10
0.00						0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.05						0.699	0.951	1.391	2.281	3.427	4.414	5.129	5.540
0.10					0.350	0.889	1.316	2.061	3.181	4.311	5.243	5.936	6.343
0.15					0.400	1.082	1.669	2.611	3.773	4.850	5.745	6.412	6.796
0.20					0.500	1.280	2.012	3.070	4.219	5.261	6.121	6.755	7.113
0.25					0.617	1.484	2.344	3.464	4.597	5.605	6.430	7.031	7.366
0.30					0.764	1.695	2.664	3.819	4.935	5.911	6.701	7.273	7.590
0.35					0.914	1.916	2.977	4.154	5.251	6.196	6.955	7.504	7.807
0.40					1.070	2.148	3.287	4.477	5.554	6.471	7.203	7.727	8.015
0.45					1.233	2.394	3.598	4.795	5.852	6.742	7.446	7.944	8.214
0.50					1.407	2.657	3.917	5.116	6.153	7.013	7.684	8.154	8.407
0.55					1.596	2.938	4.245	5.443	6.456	7.280	7.916	8.357	8.591
0.60					1.804	3.243	4.589	5.781	6.758	7.543	8.143	8.554	8.768
0.65					2.040	3.576	4.954	6.125	7.059	7.802	8.364	8.745	8.939
0.70					2.314	3.941	5.341	6.470	7.355	8.056	8.581	8.931	9.101
0.75				0.175	2.634	4.347	5.737	6.810	7.646	8.305	8.793	9.106	9.248
0.80				0.625	3.015	4.794	6.136	7.144	7.932	8.550	8.994	9.265	9.376
0.85				1.125	3.468	5.262	6.524	7.468	8.212	8.783	9.175	9.402	9.485
0.90				1.650	3.998	5.727	6.896	7.782	8.478	8.992	9.331	9.520	9.580
0.95				2.205	4.564	6.168	7.247	8.078	8.715	9.173	9.466	9.621	9.661
1.00			0.000	2.893	5.111	6.573	7.574	8.342	8.921	9.327	9.580	9.708	9.733
1.10		0.366	1.867	4.190	6.019	7.251	8.107	8.760	9.245	9.571	9.763	9.849	9.852
1.20	0.585	1.889	3.033	5.059	6.639	7.726	8.480	9.055	9.476	9.748	9.897	9.955	9.947
1.30	1.341	2.660	3.746	5.573	7.027	8.037	8.730	9.258	9.638	9.874	9.996	10.037	10.023
1.40	1.840	3.145	4.172	5.882	7.272	8.236	8.895	9.394	9.749	9.963	10.068	10.100	10.086
1.50	2.206	3.466	4.447	6.086	7.430	8.358	8.995	9.479	9.821	10.022	10.118	10.147	10.138
1.70	2.748	3.903	4.810	6.341	7.591	8.446	9.063	9.540	9.877	10.074	10.170	10.207	10.215

Note : Half-breadths of waterlines are expressed in metres.

Waterline heights are given as fractions of design full-load draft : 7,158 m

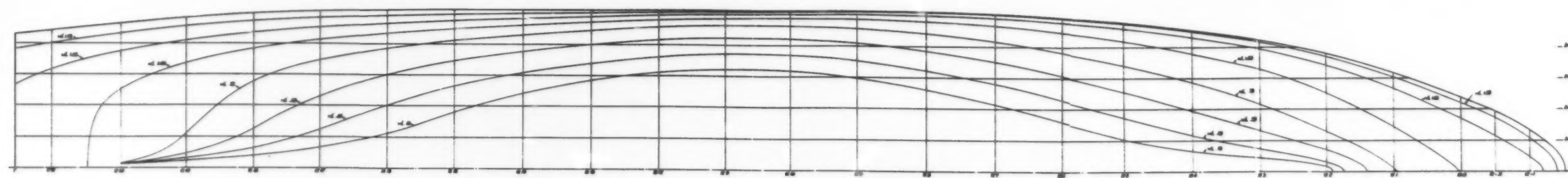
WATER- LINES.	STATIONS NUMBERED FROM THE BOW (FP DESIGNATED AS STATION 0 AND AP AS STATION 20)												
	10	11	12	13	14	15	16	17	18	19	20	21	21.51
0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
0.05	5.540	5.637	5.385	4.742	3.652	2.348	1.418	0.922	0.646	0.426	0.300		
0.10	6.343	6.429	6.198	5.664	4.809	3.578	2.215	1.300	0.800	0.485	0.300		
0.15	6.796	6.867	6.642	6.154	5.406	4.347	2.932	1.683	0.956	0.532	0.300		
0.20	7.113	7.170	6.951	6.495	5.813	4.867	3.541	2.073	1.119	0.581	0.300		
0.25	7.366	7.414	7.206	6.776	6.140	5.271	4.046	2.474	1.289	0.633	0.300		
0.30	7.590	7.637	7.441	7.036	6.436	5.621	4.480	2.888	1.470	0.688	0.300		
0.35	7.807	7.851	7.667	7.285	6.720	5.951	4.873	3.317	1.669	0.746	0.300		
0.40	8.015	8.057	7.883	7.524	6.992	6.268	5.246	3.750	1.896	0.809	0.300		
0.45	8.214	8.253	8.089	7.753	7.256	6.577	5.609	4.174	2.174	0.878	0.300		
0.50	8.407	8.441	8.287	7.974	7.512	6.882	5.974	4.595	2.531	0.955	0.300		
0.55	8.591	8.620	8.476	8.186	7.761	7.182	6.342	5.032	2.973	1.045	0.300		
0.60	8.768	8.792	8.657	8.390	8.004	7.479	6.716	5.500	3.447	1.161	0.300		
0.65	8.939	8.956	8.820	8.582	8.232	7.764	7.094	6.005	4.017	1.330	0.300		
0.70	9.101	9.107	8.980	8.750	8.429	8.011	7.431	6.522	4.732	1.639	0.300		
0.75	9.248	9.238	9.111	8.893	8.597	8.219	7.709	6.949	5.556	2.195	0.300		
0.80	9.376	9.352	9.224	9.017	8.743	8.399	7.944	7.292	6.206	3.324	0.300		
0.85	9.485	9.450	9.323	9.127	8.873	8.558	8.148	7.577	6.681	4.859	0.300		
0.90	9.580	9.535	9.411	9.226	8.990	8.701	8.330	7.823	7.059	5.714	0.695		
0.95	9.661	9.610	9.490	9.316	9.097	8.832	8.495	8.041	7.377	6.290	3.529		
1.00	9.733	9.678	9.562	9.399	9.196	8.953	8.647	8.239	7.653	6.738	5.018		
1.10	9.852	9.794	9.689	9.548	9.377	9.174	8.921	8.588	8.123	7.431	6.334	3.652	
1.20	9.947	9.891	9.800	9.681	9.540	9.373	9.166	8.894	8.516	7.967	7.153	5.787	4.354
1.30	10.023	9.974	9.898	9.802	9.688	9.556	9.389	9.168	8.858	8.409	7.763	6.802	6.052
1.40	10.086	10.046	9.987	9.914	9.827	9.726	9.596	9.418	9.162	8.786	8.251	7.511	6.999
1.50	10.138	10.109	10.069	10.018	9.958	9.886	9.790	9.649	9.437	9.114	8.656	8.056	7.674
1.70	10.215	10.216	10.214	10.208	10.198	10.181	10.144	10.065	9.916	9.661	9.018	8.852	8.608

Note : Half-breadths of waterlines are expressed in metres.

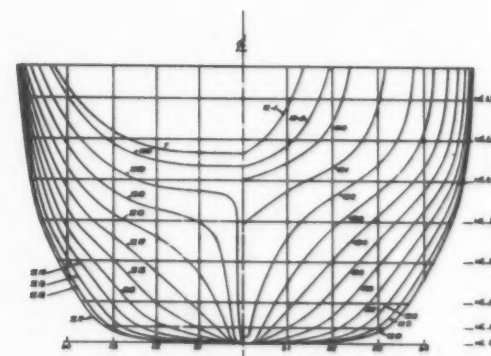
Waterline heights are given as fractions of design full-load draft : 7,158 m

EXPONENT = 1.0

BOW "A"



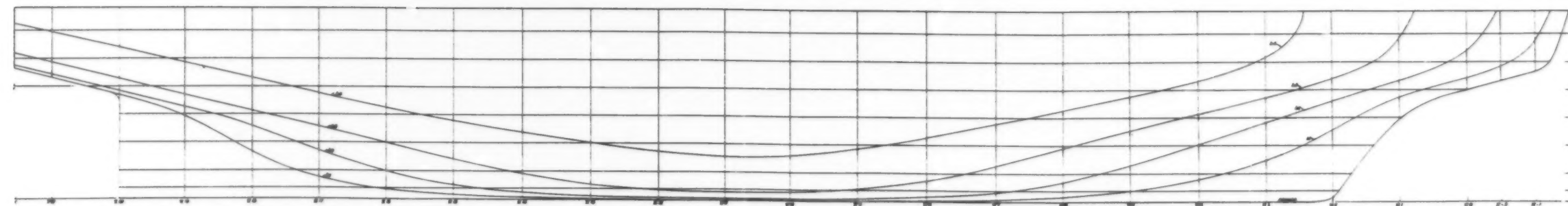
'WATERLINES'



'BODY PLAN'

'MAIN PARTICULARS'

LENGTH OVERALL	: 101.26 M
LENGTH B.P.	: 87.94 M
BEAM	: 20.43 M
DEPTH	: 12.19 M
DRAFT	: 7.158 M
DISPLACEMENT	: 6687 TONS
SPEED	: 18 KNOTS



'PROFILE & BUTTOCKS'

DONALD CARRER & ASSOCIATES, CONSULTING

PROJECT: ICEBREAKER CONCEPTUAL DESIGN

(EXHIBIT IN PLANS SECTION 1.0)

'LINES PLAN'

DESIGN: RILEY BERNARD
NARRATIVE
DR. J. J. BERNARD, & ASSOCIATES
CHIEF: DR.
TEL: (408) 642-1000

DATE: NOVEMBER 1980

SCALE: 1" = 10'

TABLE OF OFFSETS HULL FORM "B" (N=1,5)

WATER- LINES.	STATIONS NUMBERED FROM THE BOW (FP DESIGNATED AS STATION 0 AND AP AS STATION 20)												
	-1	-0.5	0	1	2	3	4	5	6	7	8	9	10
0.00						0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.05						0.745	0.998	1.430	2.298	3.419	4.395	5.114	5.534
0.10					0.350	0.980	1.401	2.117	3.187	4.282	5.211	5.925	6.356
0.15					0.425	1.216	1.784	2.670	3.760	4.796	5.697	6.399	6.821
0.20					0.550	1.453	2.147	3.124	4.181	5.178	6.054	6.736	7.142
0.25					0.688	1.693	2.492	3.504	4.529	5.494	6.343	7.002	7.390
0.30					0.878	1.936	2.819	3.840	4.836	5.770	6.592	7.228	7.600
0.35					1.071	2.184	3.132	4.151	5.118	6.024	6.820	7.434	7.792
0.40					1.270	2.439	3.436	4.445	5.386	6.266	7.038	7.630	7.972
0.45					1.476	2.703	3.734	4.731	5.648	6.503	7.251	7.819	8.145
0.50					1.691	2.976	4.031	5.013	5.908	6.740	7.462	8.004	8.312
0.55					1.920	3.260	4.330	5.297	6.172	6.980	7.674	8.188	8.477
0.60					2.165	3.556	4.635	5.586	6.442	7.226	7.889	8.374	8.640
0.65					2.433	3.865	4.947	5.885	6.721	7.479	8.111	8.562	8.804
0.70					2.726	4.190	5.273	6.194	7.012	7.744	8.342	8.757	8.971
0.75				0.200	3.046	4.533	5.612	6.518	7.317	8.023	8.584	8.958	9.133
0.80				0.750	3.399	4.898	5.969	6.859	7.644	8.323	8.840	9.153	9.278
0.85				1.275	3.785	5.287	6.344	7.223	7.995	8.642	9.085	9.323	9.402
0.90				1.850	4.205	5.698	6.740	7.613	8.370	8.940	9.292	9.465	9.508
0.95				2.394	4.658	6.128	7.157	8.024	8.713	9.187	9.461	9.584	9.600
1.00			0.000	3.002	5.132	6.570	7.588	8.391	8.990	9.384	9.600	9.685	9.682
1.10		0.370	1.914	4.105	6.083	7.389	8.244	8.901	9.378	9.671	9.812	9.850	9.822
1.20	0.588	1.868	2.947	5.024	6.770	7.860	8.618	9.207	9.626	9.866	9.967	9.980	9.942
1.30	1.312	2.584	3.679	5.583	7.114	8.123	8.842	9.401	9.790	10.003	10.084	10.086	10.046
1.40	1.808	3.112	4.152	5.887	7.316	8.282	8.983	9.526	9.900	10.101	10.175	10.175	10.139
1.50	2.198	3.461	4.444	6.086	7.447	8.380	9.069	9.604	9.973	10.172	10.247	10.251	10.224
1.70	2.748	3.903	4.810	6.341	7.591	8.465	9.137	9.668	10.042	10.252	10.346	10.375	10.374

Note : Half-breadths of waterlines are expressed in metres.
Waterline heights are given as fractions of design full-load draft : 7,158 m

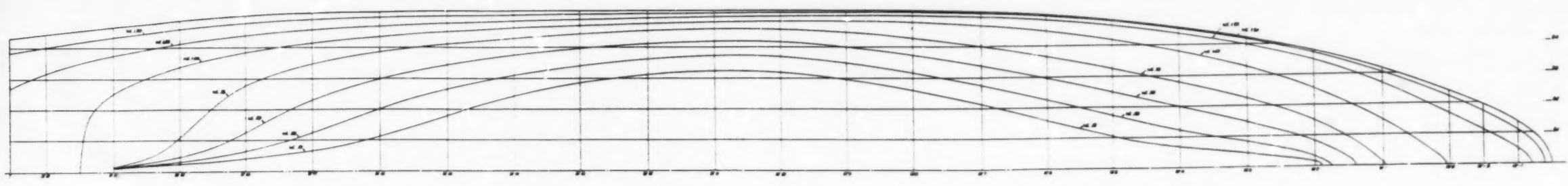
WATER- LINES.	STATIONS NUMBERED FROM THE BOW (FP DESIGNATED AS STATION 0 AND AP AS STATION 20)												
	10	11	12	13	14	15	16	17	18	19	20	21	21.51
0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
0.05	5.534	5.638	5.388	4.742	3.651	2.348	1.418	0.922	0.646	0.426	0.300		
0.10	6.356	6.455	6.224	5.680	4.815	3.579	2.216	1.300	0.800	0.485	0.300		
0.15	6.821	6.909	6.683	6.181	5.418	4.350	2.933	1.683	0.956	0.532	0.300		
0.20	7.142	7.220	6.999	6.527	5.828	4.873	3.542	2.073	1.119	0.581	0.300		
0.25	7.390	7.461	7.248	6.804	6.154	5.277	4.048	2.474	1.289	0.633	0.300		
0.30	7.600	7.667	7.468	7.052	6.444	5.625	4.481	2.888	1.470	0.688	0.300		
0.35	7.792	7.858	7.673	7.285	6.718	5.950	4.874	3.317	1.669	0.746	0.300		
0.40	7.972	8.037	7.867	7.508	6.981	6.263	5.245	3.751	1.896	0.809	0.300		
0.45	8.145	8.208	8.052	7.722	7.235	6.567	5.608	4.175	2.175	0.878	0.300		
0.50	8.312	8.373	8.231	7.930	7.483	6.867	5.970	4.595	2.531	0.955	0.300		
0.55	8.477	8.534	8.406	8.133	7.727	7.165	6.336	5.031	2.973	1.045	0.300		
0.60	8.640	8.692	8.577	8.332	7.968	7.461	6.709	5.499	3.447	1.161	0.300		
0.65	8.804	8.850	8.745	8.524	8.199	7.749	7.088	6.004	4.017	1.330	0.300		
0.70	8.971	9.004	8.902	8.697	8.402	8.000	7.428	6.521	4.732	1.639	0.300		
0.75	9.133	9.144	9.038	8.846	8.576	8.214	7.711	6.952	5.556	2.195	0.300		
0.80	9.278	9.265	9.158	8.977	8.728	8.400	7.953	7.300	6.209	3.324	0.300		
0.85	9.402	9.371	9.263	9.093	8.865	8.566	8.164	7.592	6.690	4.860	0.300		
0.90	9.508	9.464	9.357	9.199	8.989	8.717	8.354	7.845	7.074	5.718	0.695		
0.95	9.600	9.547	9.444	9.297	9.104	8.856	8.527	8.072	7.398	6.298	3.529		
1.00	9.682	9.624	9.525	9.389	9.212	8.987	8.688	8.278	7.682	6.751	5.020		
1.10	9.822	9.761	9.672	9.557	9.411	9.226	8.981	8.646	8.167	7.454	6.340	3.652	
1.20	9.942	9.882	9.806	9.711	9.593	9.444	9.245	8.971	8.578	8.002	7.164	5.788	4.354
1.30	10.046	9.993	9.930	9.855	9.763	9.646	9.489	9.265	8.937	8.455	7.778	6.803	6.052
1.40	10.139	10.095	10.047	9.991	9.923	9.837	9.716	9.535	9.259	8.844	8.272	7.513	6.999
1.50	10.224	10.192	10.158	10.120	10.075	10.018	9.931	9.787	9.552	9.185	8.683	8.058	7.674
1.70	10.374	10.368	10.364	10.362	10.360	10.356	10.328	10.246	10.069	9.756	9.332	8.856	8.608

Note : Half-breadths of waterlines are expressed in metres.
Waterline heights are given as fractions of design full-load draft : 7,158 m

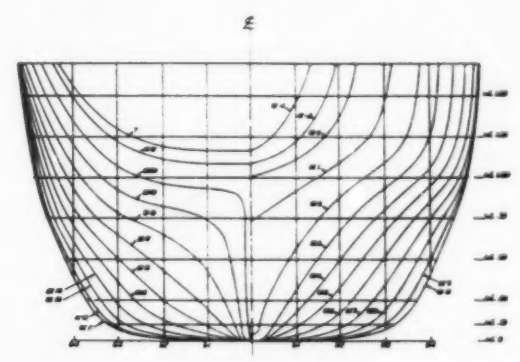


EXPONENT - 1,5

BOW "B"



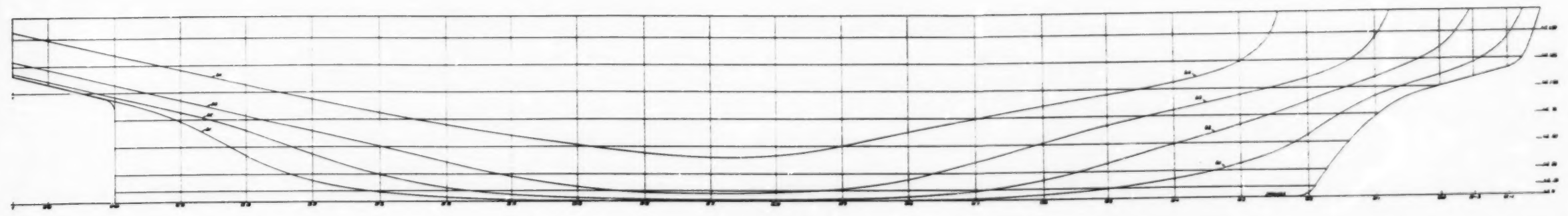
'WATERLINES'



'BODY PLAN'

'MAIN PARTICULARS'

LENGTH OVERALL	: 101.25 M
LENGTH B.P.	: 87.94 M
BEAM	: 20.75 M
DEPTH	: 12.19 M
DRAFT	: 7.158 M
DISPLACEMENT	: 8663 TONS
SPEED	: 18 KNOTS



'PROFILE & BUTTOCKS'

DONALD CARTER & ASSOCIATES, CONSULTANTS

PROJECT

ICEBREAKER CONCEPTUAL DESIGN

(EXPONENT 1.5 PLAN PROVISIONS)

'LINES PLAN'

DESIGN: PAULINE CHEN, DONALD CARTER, DONALD CARTER & ASSOCIATES, 4000 BROADWAY, NEW YORK, NY 10018

DATE: NOVEMBER 1999

SCALE: 1:100

PLATE: 101

TABLE OF OFFSETS HULL FORM "C" (N=2,0)

WATER- LINES.	STATIONS NUMBERED FROM THE BOW (FP DESIGNATED AS STATION 0 AND AP AS STATION 20)												
	-1	-0.5	0	1	2	3	4	5	6	7	8	9	10
0.00						0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.05						0.723	0.966	1.391	2.266	3.416	4.433	5.195	5.645
0.10					0.300	0.936	1.341	2.048	3.117	4.230	5.201	5.964	6.432
0.15					0.425	1.150	1.698	2.569	3.651	4.707	5.660	6.425	6.897
0.20					0.525	1.365	2.034	2.988	4.031	5.055	5.997	6.757	7.224
0.25					0.641	1.582	2.350	3.329	4.338	5.339	6.267	7.017	7.476
0.30					0.815	1.802	2.645	3.623	4.605	5.584	6.497	7.235	7.685
0.35					0.993	2.025	2.922	3.892	4.848	5.808	6.705	7.430	7.872
0.40					1.177	2.253	3.188	4.145	5.079	6.021	6.902	7.612	8.044
0.45					1.366	2.488	3.449	4.392	5.307	6.232	7.096	7.788	8.206
0.50					1.564	2.730	3.710	4.639	5.538	6.447	7.291	7.960	8.361
0.55					1.773	2.984	3.976	4.894	5.781	6.673	7.492	8.133	8.512
0.60					1.996	3.251	4.254	5.165	6.041	6.914	7.703	8.310	8.662
0.65					2.240	3.538	4.551	5.459	6.325	7.175	7.928	8.493	8.813
0.70					2.510	3.849	4.877	5.782	6.638	7.459	8.168	8.685	8.966
0.75				0.175	2.810	4.193	5.238	6.141	6.983	7.770	8.427	8.887	9.120
0.80				0.600	3.151	4.584	5.640	6.540	7.366	8.112	8.705	9.091	9.265
0.85				1.100	3.542	5.027	6.086	6.980	7.787	8.476	8.979	9.280	9.396
0.90				1.650	3.997	5.516	6.573	7.462	8.226	8.823	9.227	9.447	9.513
0.95				2.285	4.509	6.038	7.093	7.945	8.626	9.126	9.440	9.591	9.617
1.00			0.000	2.936	5.049	6.575	7.586	8.362	8.964	9.381	9.621	9.717	9.711
1.10		0.224	1.835	4.150	6.078	7.433	8.303	8.972	9.464	9.766	9.903	9.924	9.875
1.20	0.542	1.992	3.177	5.109	6.747	7.928	8.740	9.358	9.791	10.027	10.105	10.085	10.016
1.30	1.607	3.010	4.062	5.716	7.126	8.227	9.008	9.598	9.999	10.201	10.250	10.212	10.138
1.40	2.307	3.645	4.590	6.068	7.366	8.413	9.170	9.740	10.123	10.311	10.353	10.316	10.248
1.50	2.736	3.998	4.887	6.293	7.524	8.525	9.256	9.809	10.183	10.372	10.423	10.400	10.348
1.70	3.155	4.328	5.185	6.548	7.696	8.607	9.277	9.795	10.167	10.387	10.491	10.526	10.529

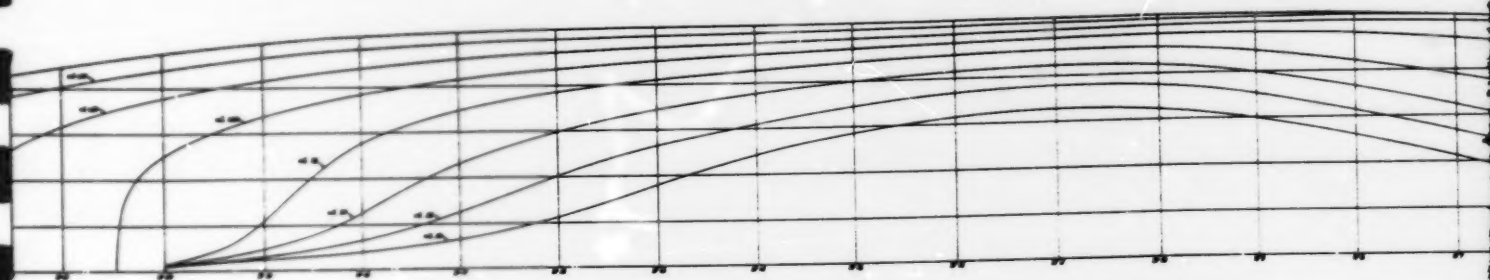
Note : Half-breadths of waterlines are expressed in metres.

Waterline heights are given as fractions of design full-load draft : 7,158 m

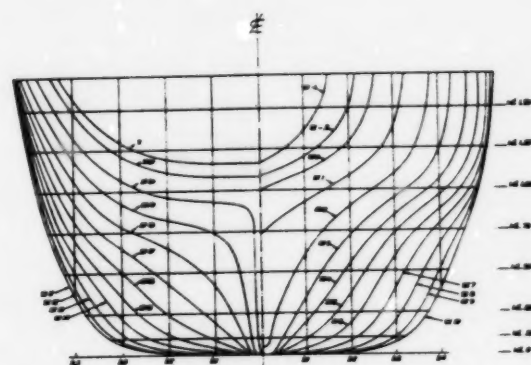
WATER- LINES.	STATIONS NUMBERED FROM THE BOW (FP DESIGNATED AS STATION 0 AND AP AS STATION 20)												
	10	11	12	13	14	15	16	17	18	19	20	21	21.51
0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
0.05	5.645	5.751	5.484	4.814	3.695	2.362	1.420	0.923	0.646	0.426	0.300		
0.10	6.432	6.543	6.300	5.732	4.844	3.593	2.219	1.300	0.800	0.485	0.300		
0.15	6.897	7.004	6.767	6.238	5.447	4.362	2.936	1.683	0.956	0.532	0.300		
0.20	7.224	7.325	7.093	6.590	5.860	4.885	3.545	2.074	1.119	0.581	0.300		
0.25	7.476	7.573	7.349	6.872	6.188	5.290	4.051	2.474	1.289	0.633	0.300		
0.30	7.685	7.782	7.570	7.121	6.479	5.639	4.485	2.889	1.470	0.688	0.300		
0.35	7.872	7.970	7.774	7.353	6.752	5.964	4.877	3.318	1.669	0.746	0.300		
0.40	8.044	8.143	7.962	7.572	7.013	6.276	5.249	3.751	1.896	0.809	0.300		
0.45	8.206	8.304	8.139	7.780	7.264	6.579	5.611	4.176	2.175	0.878	0.300		
0.50	8.361	8.457	8.307	7.979	7.508	6.877	5.972	4.595	2.531	0.955	0.300		
0.55	8.512	8.603	8.468	8.171	7.745	7.171	6.338	5.031	2.973	1.045	0.300		
0.60	8.662	8.745	8.623	8.357	7.977	7.463	6.710	5.499	3.447	1.161	0.300		
0.65	8.813	8.885	8.773	8.536	8.200	7.747	7.087	6.004	4.017	1.330	0.300		
0.70	8.966	9.022	8.915	8.701	8.400	7.998	7.427	6.521	4.732	1.639	0.300		
0.75	9.120	9.151	9.044	8.846	8.573	8.213	7.712	6.954	5.556	2.195	0.300		
0.80	9.265	9.269	9.160	8.976	8.728	8.402	7.957	7.305	6.212	3.324	0.300		
0.85	9.396	9.376	9.266	9.094	8.868	8.572	8.172	7.601	6.698	4.862	0.300		
0.90	9.513	9.473	9.363	9.204	8.996	8.728	8.367	7.860	7.088	5.727	0.695		
0.95	9.617	9.562	9.454	9.306	9.117	8.872	8.545	8.092	7.420	6.317	3.529		
1.00	9.711	9.645	9.540	9.403	9.230	9.008	8.712	8.305	7.712	6.781	5.031		
1.10	9.875	9.797	9.701	9.585	9.443	9.260	9.017	8.686	8.214	7.507	6.377	3.654	
1.20	10.016	9.936	9.851	9.755	9.640	9.492	9.296	9.026	8.643	8.080	7.226	5.805	4.354
1.30	10.138	10.064	9.993	9.917	9.826	9.710	9.553	9.335	9.021	8.557	7.867	6.836	6.053
1.40	10.248	10.186	10.129	10.071	10.004	9.917	9.797	9.622	9.363	8.971	8.388	7.561	7.000
1.50	10.348	10.302	10.261	10.221	10.175	10.116	10.028	9.890	9.676	9.337	8.825	8.122	7.675
1.70	10.529	10.524	10.517	10.510	10.502	10.490	10.459	10.383	10.233	9.960	9.528	8.950	8.609

Note : Half-breadths of waterlines are expressed in metres.

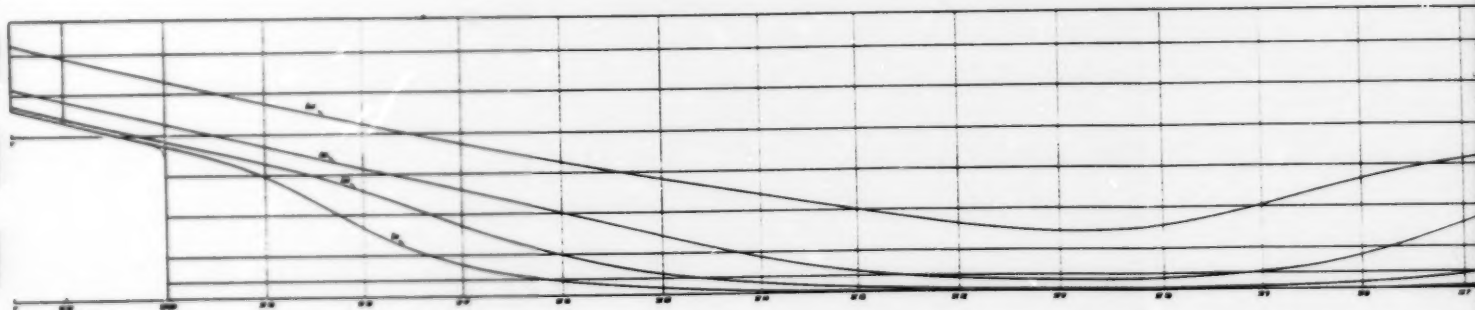
Waterline heights are given as fractions of design full-load draft : 7,158 m



'WATERLINES'



'BODY PLAN'



'PROFILE & BUTTOCKS'

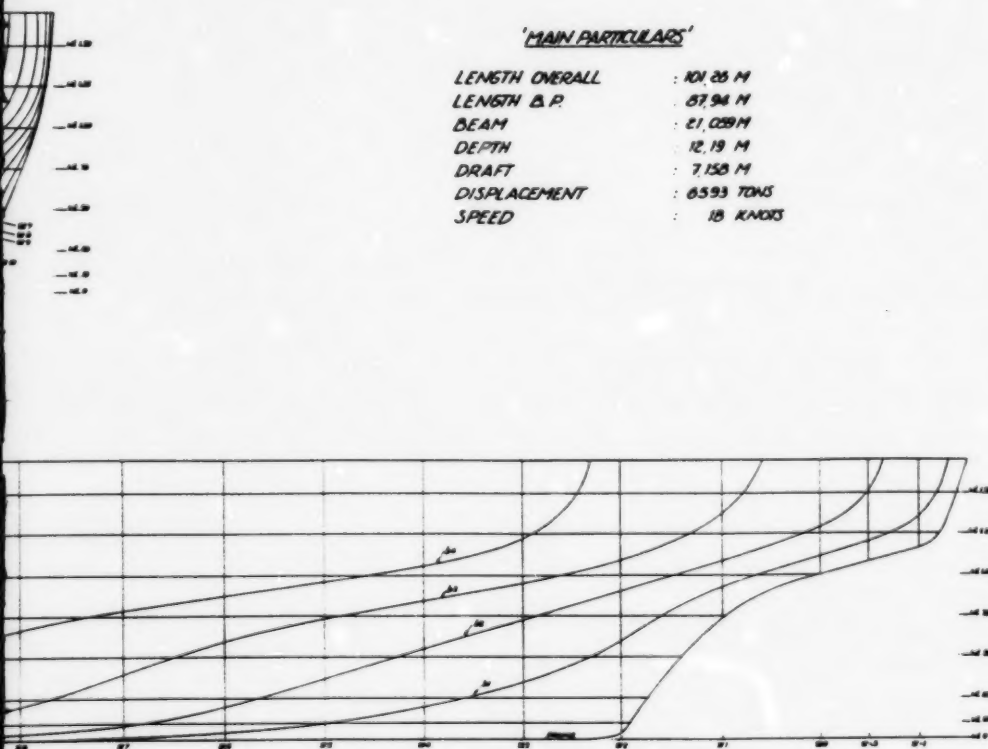
EXPONENT-2.0

BOW "C"



'MAIN PARTICULARS'

LENGTH OVERALL	: 101.25 M
LENGTH B.P.	: 87.94 M
BEAM	: 21.029 M
DEPTH	: 12.19 M
DRAFT	: 7.153 M
DISPLACEMENT	: 6593 TONS
SPEED	: 18 KNOTS



DONALD CARTER & ASSOCIATES, CONSULTANTS

PROJECT
ICEBREAKER CONCEPTUAL DESIGN

(EXPONENT ON PLAIN PROJECTION, 2.0)

"LINES PLAN"

DESIGN
APPROVED BY: [Signature]
DATE: [Date]
SCALE: 1:100

DATE: [Date]
SCALE: 1:100

8.: PRACTICAL APPLICATIONS

Our analytical treatment of the icebreaking mechanisms allows us to determine the individual force created at each point of contact along the waterplane as a function of the bow geometry and the material properties. Using this approach we have developed, in the course of the study, four (4) computer programs respectively called: DCARTER, WAAS, OPTIBOW, and RETROFIT. These programs are presently in the process of being validated at the Transportation Development Centre and the Canadian Coast Guard. They are written in the concept of user friendly programs. They may be used for either full-scale trials or model tests in ice of any arbitrary properties.

8.1.: "DCARTER" PROGRAM

"DCARTER" is a program for predicting the ice resistance and performance of a ship, with a so-called conventional icebreaker hull form, moving continuously through a homogeneous level ice field of constant thickness and mechanical properties, without any internal pressure.

8.2.: "WAAS" PROGRAM

The program "WAAS" evaluates the level ice resistance of ships with "Waas" type bows moving continuously in uniform ice.

8.3.: "OPTIBOW" PROGRAM

"OPTIBOW" is a program for generating preliminary lines for efficient icebreaking bow forms. These preliminary lines may then be used as input to any standard hull definition programs.

8.4.: "NEWBOW" PROGRAM

"NEWBOW" defines a waterline that both satisfies the geometrical constraints at any particular cut location along the forebody section and minimizes the ice resistance.

CONCLUSIONS

The work reported herein and in previous phases represents a pioneering and ambitious attempt to further understand and model the complex interactions which occur at the ship-ice interface.

The study offers a totally new analytical approach to the assessment of the resistance of sheet ice to the motion of a ship instead of one based on the theories of Kashtelyan followed by most investigators.

The geometry of the contact area is analyzed in great detail and a new ice failure criterion is derived. This ice failure criterion takes into consideration both the variation of material parameters across the plate thickness and the modes of failure: bending, buckling, crushing, and shearing.

The procedures of analysis consider the individual forces acting at each discrete point along the waterplane and add up their longitudinal components to determine the total level ice resistance.

A computer program developed to facilitate the problem solution allows a quick evaluation of the ice performance of existing ships and proposed new designs.

Correlation of the math model results with full scale trial and model test data appears quite good, and certainly better than all other predictors. This concordance seems to justify the necessary simplifying assumptions made in the formulation of the problem.

The math model developed is sensitive to the various principal ship and ice parameters involved in breaking and moving through level ice and provides the ship designer with a meaningful design tool for optimizing ice passage capability.

Optimization on the sole basis of higher icebreaking ability results in the development of rounded or square bow forms with near 0°-stem angle and near 90°-flare angle.

Unfortunately, for such extreme shape bow forms, both the open-water resistance and the seakeeping performance, especially slamming, are much poorer than for conventional icebreaker bow forms. Due to this fact, the non-shipshaped designs may be considered only for breaking thick ice in sheltered areas where rough open-water crossings are scarce.

CONCLUSIONS (Cont'd)

Considering the usual mission profile of icebreakers, it appears obvious that the "optimum" bow should be a good compromise between:

- 1.: Level icebreaking capability;
- 2.: Performance in other ice conditions;
- 3.: Hydrodynamic behavior.

An ideal relationship between the waterline and flare angles is identified and a second computer program is written to define shiplike designs that offer excellent compromise between the three above constraints.

In order to illustrate the lines generation process, a series of 3 preliminary bow forms are presented. The unfair lines are then used as input data in the program MACSURF to generate 3 conceptual bow forms.

The predicted level ice resistance for the 3 proposed bow forms shows a significant improvement over the R-Class icebreaker without unduly affecting the seakeeping performance, as analytically assessed by the ship motion program "SHIPMO4".

In view of the operational benefits, comparative open water performance together with significant improvements of the icebreaking performance, consideration should be given to running a model test program to assess the effectiveness of the proposed bows and to validate the math model as a design tool.

REFERENCES

- Albery A.C.R., Pullerits E., Schmitt E., Ellis B., 1984, "M.V. ARCTIC Ice Transitting Performance - Continuous Mode", Report TP-5170E, prepared for Transportation Development Centre, Montreal.
- Baird A.V., Kotras T.V., 1982, "Development of a Model for Predicting Ship Performance in Level Ice", ARCTEC report 583E, October 1982.
- Baker D.N., 1984, "Redesign of the M.V. ARCTIC Bow - Design and Model Testing" Report TP-5456E prepared for Transportation Development Centre by Melville Shipping Ltd, November 1984.
- Carter D.S., 1983, "Ship Resistance to Continuous Motion in Level Ice", Report 3679E prepared for Transportation Development Centre, Montreal, March 1983.
- Carter D.S., 1985, "Ice Forces on Fixed Structures and Ship Hulls" Report TP-7457E prepared for Transportation Development Centre, Montreal.
- Carter D.S., 1987, "Mathematical Model for Predicting Ice-breaker Performance" Report TP-8531E prepared for Transportation Development Centre, Montreal.
- Edwards R.Y.Jr., Lewis J.W., Wheaton J.W., Coburn J.Jr., 1972, "Full-Scale and Model Tests of a Great Lakes Ice-breaker" SNAME paper No.5 presented at the Annual Meeting, New York, Transactions Vol. 80, Nov. 1972
- Edwards R.Y., Major R.A., Kim J.K., German J.G., Lewis J.W., 1976 "Influence of Major Characteristics of Icebreaker Hulls on their Powering Requirements and Maneuverability" Paper No. 12, SNAME Annual Meeting, New York, SNAME Transactions Vol. 84, November 1976.
- Edwards R.Y., Dunne M.A., Comfort G., Bulat V., Johnson B., 1981 "Results of Full Scale Trials in Ice of CCGS Radisson" Proceedings Sixth Ship Technology and Research STAR Symposium SNAME, Ottawa, June 1981
- Enkvist E., 1972, "On the Ice Resistance Encountered by Ships Operating in the Continuous Mode of Icebreaking" The Swedish Academy of Engineering Sciences in Finland Report No.24, Helsinki.

REFERENCES (Cont'd)

- Enkvist E., 1983, "A Survey of the Submersion and Breaking Components of Level Ice Resistance to Ships" The 7th International Conference in Port and Ocean Engineering under Arctic Conditions, Vol. 1, Helsinki.
- Enkvist E., Mustamaki E., 1986 "Model and Full-Scale Tests with an Innovative Icebreaker Bow" Paper presented at the SNAME Annual Meeting, New York, Nov. 1986.
- Everest J.T., Hogben N., 1969, "A Theoretical and Experimental Study of the Wavemaking of Hovercraft of Arbitrary Planform and Angle of Yaw" Royal Inst. Naval Architects, Paper (1969).
- Glen I.F., Abdelnour R., Steele M., 1989, "Modification and Testing of a Segmented Model of an Icebreaker to Evaluate Ice Resistance Mathematical Models" Report TP-9849E prepared for Transportation Development Centre, Montreal.
- Gold L.W., 1988, "On the Elasticity of Ice Plates" Canadian Journal of Civil Engineering, Vol. 15, No. 6, December 1988.
- Kashteljan V.I., Poznjak I.I., Ryvlin A.J., 1968, "Ice Resistance to Motion of a Ship", Sudostroenie, Leningrad, (Translation)
- Kendrick A., and Carter J., 1988, "CCGS Louis S. St. Laurent Mid-Life Modernization Design Studies" Marine Technology and SNAME News, Vol. 25, Number 2, April 1988
- Kerr A.D., and Palmer W.T., 1972, "The Deformation and Stresses in Floating Ice Plates" Acta Mechanica, Vol. 15, No. 1-2, pp. 57-72
- Kloppenburg M., 1975, "Ice Resistance of a Cargo Vessel in the Continuous Mode of Icebreaking. Tests of Three Geosim Models in Ice" SNAME Ice Tech. Symposium, Montreal, April 1975.
- Korzhavin K.N., 1962, "Action of Ice on Engineering Structures" English Translation US CRREL Draft Translation No. 260, 1970

REFERENCES (Cont'd)

- Lamb H., 1932, "Hydrodynamics" Cambridge University Press, 6th Edition, 1932
- Lewis J.W., Edwards R.Y.Jr., 1970, "Methods of Predicting Icebreaking and Ice Resistance Characteristics of Icebreakers" Paper No.5, SNAME Annual Meeting, New York, November 1970.
- Lewis J.W., Bulat V., Glen I.F., Kotras T., 1982, "Development of a Semi-Empirical Model for Predicting Resistance and Determining Thrust Requirements for Ships in Level Ice" Report prepared for Transportation Development Centre by ARCTEC, ACL Report 444C.
- Melberg L.C., Lewis J.W., Edwards R.Y.Jr., Taylor R.G., Voelker R.P., 1970, "The Design of Polar Icebreakers", SNAME Transactions, Vol.78, April 1970.
- Michailidis M., Murdey D.C., 1981, "Performance of CCGS Franklin in Lake Melville, 1980." Proceedings Sixth Ship Technology and Research (STAR) Symposium, SNAME, Ottawa, June 1981.
- Milano V.R., 1973, "Ship Resistance to Continuous Motion in Ice" Proc. SNAME Annual Meeting, New York, November 1973
- Milano V.R., 1983, "Comparison of Several Analytical Models for the Prediction of Total Ship Resistance in Level Ice - A Special Report for the ITTC ICE COMMITTEE" Report prepared by Dr. V.R. Milano, September 1983.
- Naegle J.N., 1980, "Ice Resistance Prediction and Motion Simulation for Ships Operating in the Continuous Mode of Icebreaking" Ph.D. Dissertation, University of Michigan.
- Nevel D.E., 1961, "The Narrow Free Infinite Wedge on an Elastic Foundation" US Army CRREL Research Report 79, July 1961
- Nevel D.E., 1979, "Bending and Buckling of a Wedge on an Elastic Foundation" IUTAM Symposium on the Physics and Mechanics of Ice, Tech. University of Denmark, Copenhagen, August 1979.

REFERENCES (Cont'd)

- Popov Y.N., Tegkayeva T.K., Faddeyev O.V., 1973, "Effect of the Lines of an Icebreaker on the Magnitude of Ice Loads" in Ice Navigation Qualities of Ships translated from Russian, US Army CRREL Draft Translation 417, 240 p.
- Poznyak I.I., Ionov B.P., 1981, "The Division of Icebreaker Resistance into Components" SNAME STAR Symposium, June 1981.
- Prandtl L., 1920, Nachr. Ges. Wiss. Gottingen, 74, 1920.
- Rose E., 1947 "Thrust Exerted by Expanding Ice Sheets" Trans. ASCE, Vol. 112, Paper No. 2314, p. 871-85.
- Runeberg R., 1889, "Steamers for Winter Navigation and Ice-breaking" Minutes of Proceedings of the Institution of Civil Engineering, Vol. 97, Part 3, Session 1889-90.
- Sorensen R.M., 1973, "Water Waves Produced by Ships" Journ. of Waterways, Harbors and Coastal Engineering Division ASCE, Vol. 99, Vol. WW2, Proc. Paper 9754, pp 245-256
- Spencer D., 1987, "Ice Model Tests on CCGS Louis S. St. Laurent - Phase 1" National Research Council of Canada, Institute for Marine Dynamics, TR-AVR-01, 19 pages.
- Tatinclaux J.C., 1984, "Model Tests in Ice of a Canadian Coast Guard R-Class Icebreaker" US Army CRREL Special Report 84-6, April 1984.
- USSR Design Standards 1976, "Loads Exerted on Hydraulic Structures by Waves, Ice and Ships" Technical Translation No. 236, Canada Institute for Scientific and Technical Information, NRC Canada, 1980.
- Vance G.P., 1975, "A Scaling System for Vessels Modeled in Ice" Paper H presented at the SNAME Ice Tech Symposium, Montreal, April 1975.